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Assessment of Snow, Glacier and Water Resources in Asia

IHP – International Hydrological Programme of UNESCO
HWRP – Hydrology and Water Resources Programme of WMO

Assessment of Snow, Glacier and Water Resources in Asia

Selected papers from the Workshop in Almaty, Kazakhstan, 2006

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Foreword

The topic of water availability and the possible effects of climate change on water resources are of paramount importance to the Central Asian countries. In the last decades, water supply security has turned out to be one of the major challenges for these countries. The supply initially ensured by snow and glaciers is increasingly being threatened by climate change. As yet, a comprehensive understanding and evaluation of the current knowledge on glaciers in Central Asia has been lacking. The present publication aims at filling this knowledge gap in the Central Asian region while contributing to transboundary cooperation in the field of research on snow and glacier hydrology.

The individual contributions of this publication are based on lectures given at the Workshop on "Snow, Glacier and Water Resources in Asia", held in November 2006 in Almaty, Kazakhstan. The workshop was jointly organized by UNESCO Almaty Cluster Office, the Regional Environmental Centre for Central Asia (CAREC), and the Institute of Geography, Republic of Kazakhstan.

All contributions underwent a peer review, and we believe that they significantly enhance the current understanding of hydrology in Central Asia in a changing climate.

The publication will serve as a contribution to the 7th Phase of the International Hydrological Programme (IHP 2008 – 2013) of UNESCO, which has endeavored to address demands arising from a rapidly changing world. Several focal areas have been identified by the IHP to address the impacts of global changes. UNESCO IHP undertakes considerable efforts to improve scientific understanding of snow and glacial changes and impacts on water resources in various parts of the world.

The set of recommendations proposed by the participants calls for a better exchange of data relevant to glacier and snow cover changes. Managing the water resources in the region in a sustainable way will be one of the major future challenges.

In this context we trust that this publication will be helpful in tackling future problems associated with water scarcity in Central Asia.

The careful editing of most of the papers by Dr. Stefan Pohl is gratefully acknowledged.

Our sincere thanks are extended to the German IHP/HWRP Secretariat for the layout and printing of this publication.

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Executive Summary

The high mountain ranges of Asia are covered by approximately 100,000 km^2 of glacier ice. They feed the great rivers of South Asia, South-east Asia, China, and the Central Asian States of the former Soviet Union. In the head watersheds of many of these major river systems the proportion of water produced by snow and ice melt is highly significant, especially for the arid lowland areas surrounding the mountain ranges, and during the summer months. The various contributions of this publication address the following questions:

1) to what extent are the river flows and regimes affected by the melting of snow, glaciers and ground ice (permafrost and buried glacier ice)?
2) What is the contribution of ice melt in particular basins?
3) Will the relative importance of snow and ice melt compared to rainfall change with global warming?
4) How long will it take for glaciers to melt out, and how different will the flow regimes of the rivers be once the ice has disappeared?

The answers to these questions vary from region to region, as the climatic and physiographic conditions are highly diverse. Generally it can be stated that the seasonal regime of the rivers originating in the mountain ranges of Central Asia show low flows in winter and relatively high flows in summer. On almost all of the rivers spring snowmelt contributes significantly to streamflow in April and May. This is economically very important as many crops are planted in this period. In the summer months of June to September liquid precipitation dominates runoff in the Tien Shan, the Qilian Shan and in the monsoon areas of the South-east. In the western Himalaya, the Karakoram and in the Pamirs the glacier melt contribution tends to be much larger as summer rainfall is considerably smaller.

Glaciers have a regulatory effect on streamflow: when annual snowfall is well below average, glaciers tend to melt more strongly and therefore partially compensate for lower precipitation. When annual snowfall is above average, glacier ice is protected by the excess snow, and water yield is high due to above-average snowmelt. Should the glaciers continue to shrink markedly in size as was the case during recent decades, this regulatory effect will diminish and the runoff regime will move towards a nival and pluvial one with a larger year-to-year variability in water yield, and as a result water delivery from the high mountain areas will be less dependable.

The volumes of water captured as permafrost and buried ice are very difficult to assess; with continued global warming permafrost and debris-covered parts of glaciers will degrade rather slowly, and it will take centuries until much of the water stored this way is released.

As a result of water being released from glacier and permafrost melt total annual flows in river systems supplying water to arid lowlands may increase by some 4 to 6%, which is a small but significant percentage, as it will persist over decades. However, this possible increase in yield needs to be seen in relation to probable increased evaporation losses due to global warming, a question that requires further attention.

During the phase of glacier degradation glacial lakes in the tongue areas of glaciers are likely to form, and these bear the danger of rapid drainage, producing glacier-lake outburst floods which may cause severe damage downstream.

Among the recommendations formulated at the workshop is the resumption of glacier and snow monitoring at high elevations, with exchange of data via a Glaciological Data Center to be located in Almaty. This data base is a prerequisite for a wise and sustainable water management.

For the editorial committee
Ludwig Braun and Gordon Young

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The elements of high mountain hydrology with special emphasis on Central Asia

Gordon Young

Introduction

The papers in this volume consider the significance of the high mountains of Central Asia as sources of water. The majority of papers included deal with Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan; that is Central Asia defined in a limited way. However, the situation of a larger group of countries including China, Pakistan, India and Nepal are also considered in order to broaden the perspective.

There are several major questions to be answered:

- To what extent are the river flows and regimes affected by snow-melt, glacier-melt and melting of ground ice (both permafrost and dead ice)?
- Does the importance of ice melt contributions to streamflow vary from basin to basin?
- Will the relative importance of snow and ice melt compared to rainfall change with global warming?
- Within each river basin how long will it take for glaciers to melt out and how different will be the flow regimes of the rivers?

Another major theme and concern especially for Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan is the fact that since the early 1990s the collection of data on meteorology, glacier mass balance and hydrology at high elevations has been drastically reduced. An output of the Workshop was a plea to reinforce data collection mechanisms so that decisions on water resources management can be based on sound field evidence.

Although not a central focus for this particular workshop the question of how many people within each river basin will be affected by changes to river regimes and to what extent their lives and livelihoods will be affected provides the underlying social and economic rationale for the papers.

Central Asia: Elements of hydrology and water resources

Mountains have been described as the ‘Water Towers’ of the world; in general they receive more precipitation than adjacent lowlands; they are the source of much of the waters flowing down the rivers. The concept of ‘Water Towers’ is, perhaps, particularly true in central Asia where the high mountain ranges feed the great rivers of the Huang He, Yangtze, Mekong, Salween, Brahmaputra, Ganges, Indus, Amu Darya, Syr Darya, Ili and the rivers of the Tarim Basin; see Figure 1.

__Figure 1__ The geography and river systems of Central, South and East Asia (from Concise Oxford Atlas)

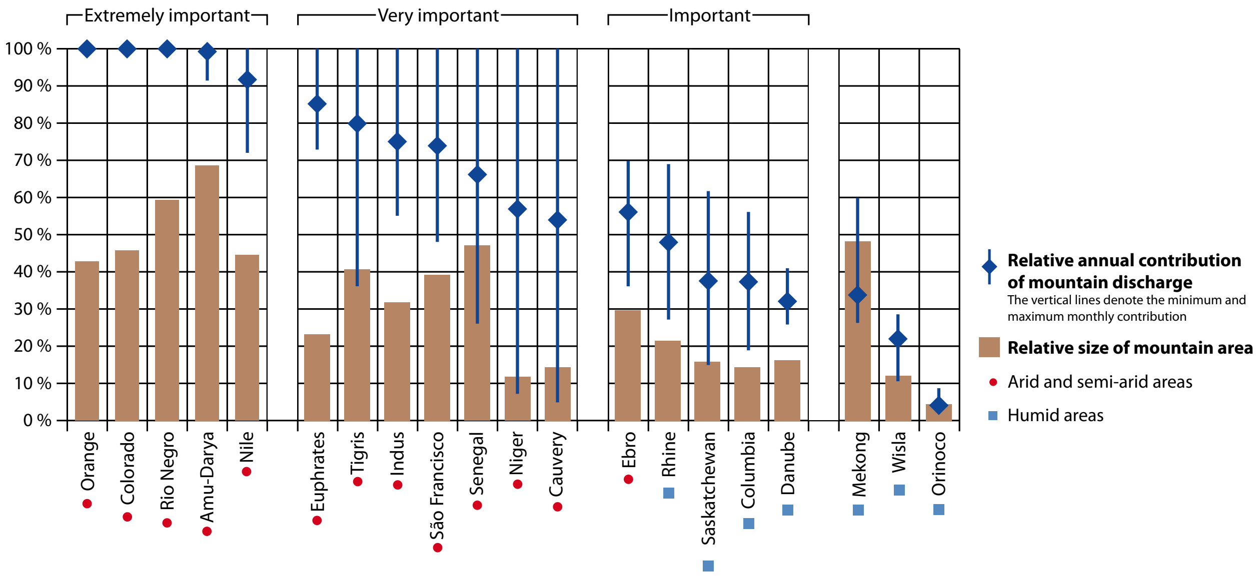


Figure 2 *The importance of mountains for water supply (From Viviroli et al 2003, courtesy of UNU and IMS)*

The significance of the contribution of mountainous areas to river flows varies considerably. The importance of the mountain contribution is greatest for those rivers flowing across arid regions after leaving the mountains; less important when the rivers discharge onto humid areas. This concept is captured in figure 2. In table 1 those rivers flowing from mountains into arid or semi-arid lands are denoted by an asterisk.

While the prime purpose of this collection of papers is not to consider the uses to which waters are assigned nor their strategic significance, it is important to realize the economic and social significance of the waters. The rivers of central Asia support more than 20% of humankind. All receive waters from high mountain areas and the lives and livelihoods of the people and the economic development within these basins is intimately and crucially linked to water

Table 1 Principal Rivers of Central Asia – Basic Statistics (* denotes a relatively arid basin) from World Resources Institute, Watersheds of the World

	Area km^2	Population x1000	Population density	Water per person m^3/year	Fragmentation index	% Forest	% Grassland	% Wetland	% Cropland	% Irrigated cropland	% Dryland	% Urban + Industrial	% loss forest cover
Lake Balkhash*	512,015	5,632	11	439	–	4.0	61.1	4.7	23.2	1.9	94.5	1.5	26.3
Syr Darya*	782,617	21,131	27	1171	High	2.4	67.4	2.0	22.2	5.4	93.7	3.2	45.4
Amu Darya*	534,739	4,813	9	3211	High	0.1	57.3	0.0	22.4	7.5	77.8	3.7	98.6
Indus*	1,081,718	178,483	165	830	–	0.4	46.4	4.2	30.0	24.1	63.1	4.6	90.1
Ganges	1,016,124	407,466	401	~2500	–	4.2	13.4	17.7	72.4	22.7	58.0	6.3	84.5
Brahmaputra	651,335	118,543	182	~2500	–	18.5	44.7	20.7	29.4	3.7	0.0	2.4	73.3
Salween	271,914	5,982	22	23,796	–	43.4	48.3	9.5	5.5	0.4	0.1	0.5	72.3
Mekong	805,604	57,198	71	8934	Medium	41.5	17.2	8.7	37.8	2.9	0.8	2.1	69.2
Yangtze	1,722,193	368,549	214	2265	Medium	6.3	28.2	3.0	47.6	7.1	2.0	3.0	84.9
Huang He*	944,970	147,415	156	361	High	1.5	60.0	1.1	29.5	7.2	79.4	5.9	78.0
Tarim*	1,152,448	8,067	7	754	High	0.0	35.3	16.3	2.3	0.6	38.6	0.3	69.3
Total		**1323,279**											

supplies. Table 1 illustrates the numbers of people involved and the land use within the basins.

As far as water resource management is concerned, two important facts should be mentioned about the contribution made by melting snow and ice. Firstly, in almost every part of the region spring snowmelt is crucial for irrigation. Secondly, glacier melt in the summer assumes greatest importance where summer precipitation is normally low or in years when normally heavy summer rains fail.

The elements of high mountain hydrology and the significance of snow and ice melt for human development

Significant proportions of annual precipitation fall as snow in most high mountain regions and, in many mountain ranges and over long periods of time, the snowfall has built up into glaciers which are semi-permanent reservoirs of water preserved as ice. In addition, in most high mountain regions and especially in those at high latitudes, there are significant reserves of water held in the ground as permafrost.

Snowpacks accumulate during the winter periods to be released as meltwaters during spring and summer giving the streams a distinct seasonal rhythm to annual flow regimes. Some rivers, particularly in monsoon climates, receive much of their snow during the summer – the snow is then melted almost immediately to contribute to streamflow.

Global warming induces glacier recession (that is water coming out of long term storage) releasing waters to the rivers and augmenting the contribution of annual precipitation. Release of water stored as glacier ice is particularly significant in years of low precipitation and during the late summer period when seasonal snowpacks have largely melted. Thus glaciers provide a buffering effect on streamflow, acting as regulators and providing insurance against times of low flow. However, while in the short term glacier melt will provide extra water to the rivers, in the longer term when those ice masses melt out, that extra water will no longer be available and the all-important buffering effect will disappear. Thus there will likely be an increase in the variability of streamflows with consequent reduction in the reliability of flows. With the diminution of the size of glaciers there will likely be a reduction in flows in the late summer period. A very important question is: for how long will shrinking glaciers deliver water extra to annual precipitation to the streams? The answer will be different from one region to another depending on glacier extent and the speed of global warming.

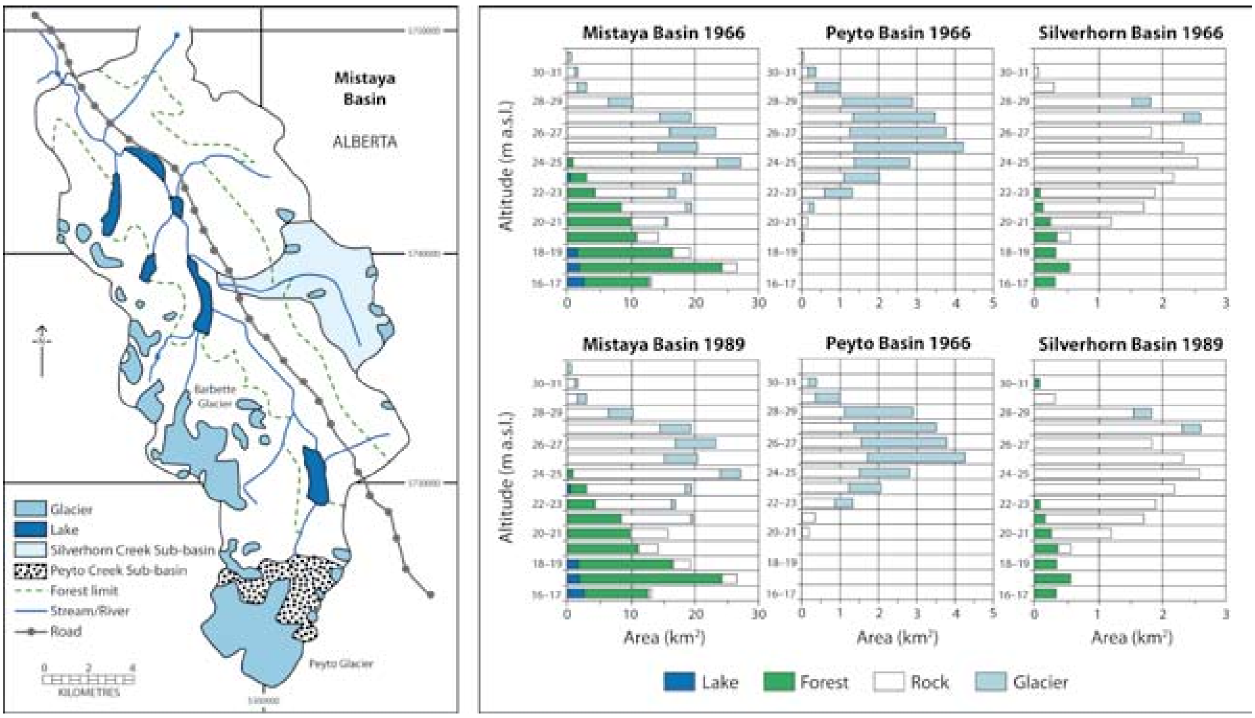


Figure 3 *The Mistaya Basin with sub-basins of Peyto Creek and Silverhorn Creek, (after Schuster and Young, 2006). (Note: elevations in hundreds of metres).*

Table 2 Summary of basin characteristics in 1989

	Mistaya	Peyto	Silverhorn
Basin area (km^2)	247.2	22.25	19.99
Glacier cover (km^2)	26.6	12.12	0.58
% glacier cover	10.8	54.50	2.90

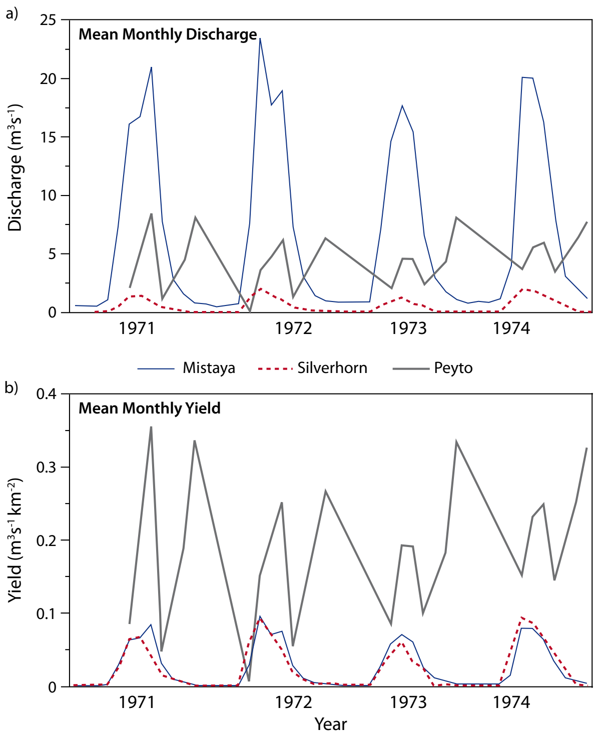


Figure 4 *Graphical illustration of a) comparative discharge and b) basin yield (i.e. discharge standardized with respect to basin area) in the basins for 1971 to 1974, (after Schuster and Young, 2006).*

Example of the Mistaya Basin, Rocky Mountains, Alberta, Canada

To illustrate the elements of high mountain hydrology reference is made to the Mistaya Basin, see figure 3.

The Mistaya basin is characterized by three major terrain types: forest in the lowest elevation zones, bare rock and glacier cover at higher elevations. The hypsographic histograms for the basin and the sub-basins are shown in figure 3.

In the 23 year period 1966–89 the Mistaya basin lost some 3.2 km^2 of its glacier cover (an 11 % loss). This areal loss translated into a volumetric loss of 340 x 10^6 m^3 water equivalent (or on average 14.8 x 10^6 m^3 per year). This glacier shrinkage represents about 6 % of mean annual runoff for the Mistaya basin.

It is instructive to compare the discharge records for the Peyto and Silverhorn Creeks. These basins are of approximately the same size but with very different glacier cover. Peak discharges in Silverhorn Creek are in June and July as a result of snowmelt; Peak discharges for Peyto Creek are in August when melting glacier ice predominates. Overall discharges for Peyto Creek are far higher than for Silverhorn Creek. Summaries of the runoff are shown on table 3 and in figure 4.

Within the Peyto basin there has been dramatic glacier shrinkage over the last decades. Figure 5 illustrates the

Table 3 Summary of hydrological records; Qm and Qi are average basin discharges on a monthly and standardized basis respectively for each year, (after Schuster and Young, 2006)

	Mistaya 1950 – 94			Silverhorn 1971 – 94			Peyto 1967 – 77		
	Qm	Coeff.	Qi	Qm	Coeff.	Qi	Qm	Coeff.	Qi
	m^3 s^{-1}	Variation	m^3 s^{-1} km^{-2}	m^3 s^{-1}	Variation	m^3 s^{-1} km^{-2}	m^3 s^{-1}	Variation	m^3 s^{-1} km^{-2}
Jan	0.72	0.19	0.003	0.05	0.02	0.003			
Feb	0.61	0.13	0.002	0.05	0.01	0.002			
Mar	0.64	0.17	0.003	0.04	0.02	0.002			
Apr	1.13	0.42	0.005	0.07	0.04	0.004			
May	6.88	2.27	0.028	0.52	0.25	0.025			
June	16.50	3.65	0.066	1.46	0.46	0.071	2.51	0.46	0.113 (67 – 77)
July	20.60	3.10	0.083	1.51	0.55	0.073	4.79	0.20	0.215 (67 – 77)
Aug	16.70	2.86	0.067	0.80	0.22	0.039	5.80	0.23	0.261 (67 – 74)
Sept	8.42	2.23	0.034	0.42	0.16	0.020	1.81	0.49	0.081 (68, 71 – 75)
Oct	3.70	1.06	0.015	0.19	0.06	0.009			
Nov	1.68	0.39	0.007	0.10	0.03	0.005			
Dec	0.98	0.16	0.004	0.07	0.02	0.003			
Mean Ann.	**7.63**	**7.68**	**0.031**	**0.44**	**0.57**	**0.021**			

Note: The Mistaya basin comprises sub-basins with very different characteristics; for particular months sub-basins show much less variability in runoff than the larger, composite basin.

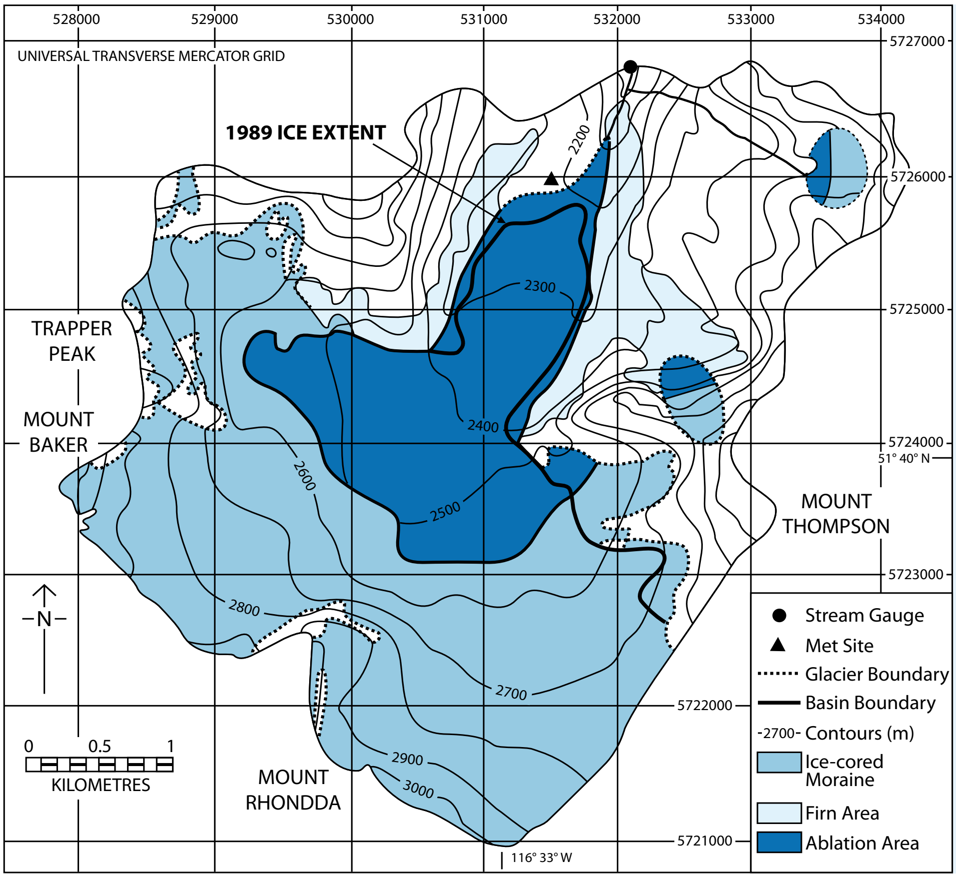


Figure 5
Map of Peyto Glacier showing terrain types and changes in glacier extent 1966–89, (after Schuster and Young, 2006).

shrinkage in the period 1966–89 amounting to a change in glacier area from 13.2 to 12.1 km^2. this represents a loss in the order of 170 x 10^6 m^3 water equivalent, (or on average 7.4 x 10^6 m^3 per year), 75 % of which was from the lowest elevations on the glacier below the 2600 m contour.

Annual variability in glacier melt contributions to discharge for Peyto Glacier are given in figure 6. In 1970 Peyto glacier experienced the most negative mass balance in the period 1966–95 while 1974 was a year of moderately positive mass balance. Snowpack depletion, glacier ice melt and firn melt were monitored over the entire glacier at stake locations throughout the summer period. Rainfall was monitored at the glacier base camp site. This allowed compilation of the maps and graphs shown in fig 6, which in turn allow interpretation of the discharge curves. During the period 1977 to the present mass balances on Peyto glacier have been consistently negative. Figure 6 also illustrates the effect of a low winter snowpack in 1970 which resulted in very fast movement of the transient snowline baring glacier ice much earlier than usual and causing a large contribution to runoff from glacier shrinkage.

Further illustration of the general role of snow and ice in the hydrology of mountain areas in general and in the Himalaya in particular is given in the paper by Singh (page 123).

These relationships in general hold for many of the high mountain regions of the world with minor modifications for local terrain types and climates. The relationships are further well illustrated in the case of the Massa and Rhone rivers in the paper by Braun and Hagg (page 36).

Example from the Karakoram

Figure 7 illustrates some of the important characteristics of large valley glaciers in the Karakoram. Of particular importance in this context are the extensive areas of debris covers on many of the glaciers in this region and in Central Asia. Melt rates in debris covered areas differ markedly from bare ice and, indeed show great variability within the debris covered areas themselves. Debris covered areas usually merge with ice-cored moraines making the definition of the glacier edge very uncertain. Release of waters from melt within ice-cored moraines can form a significant portion of

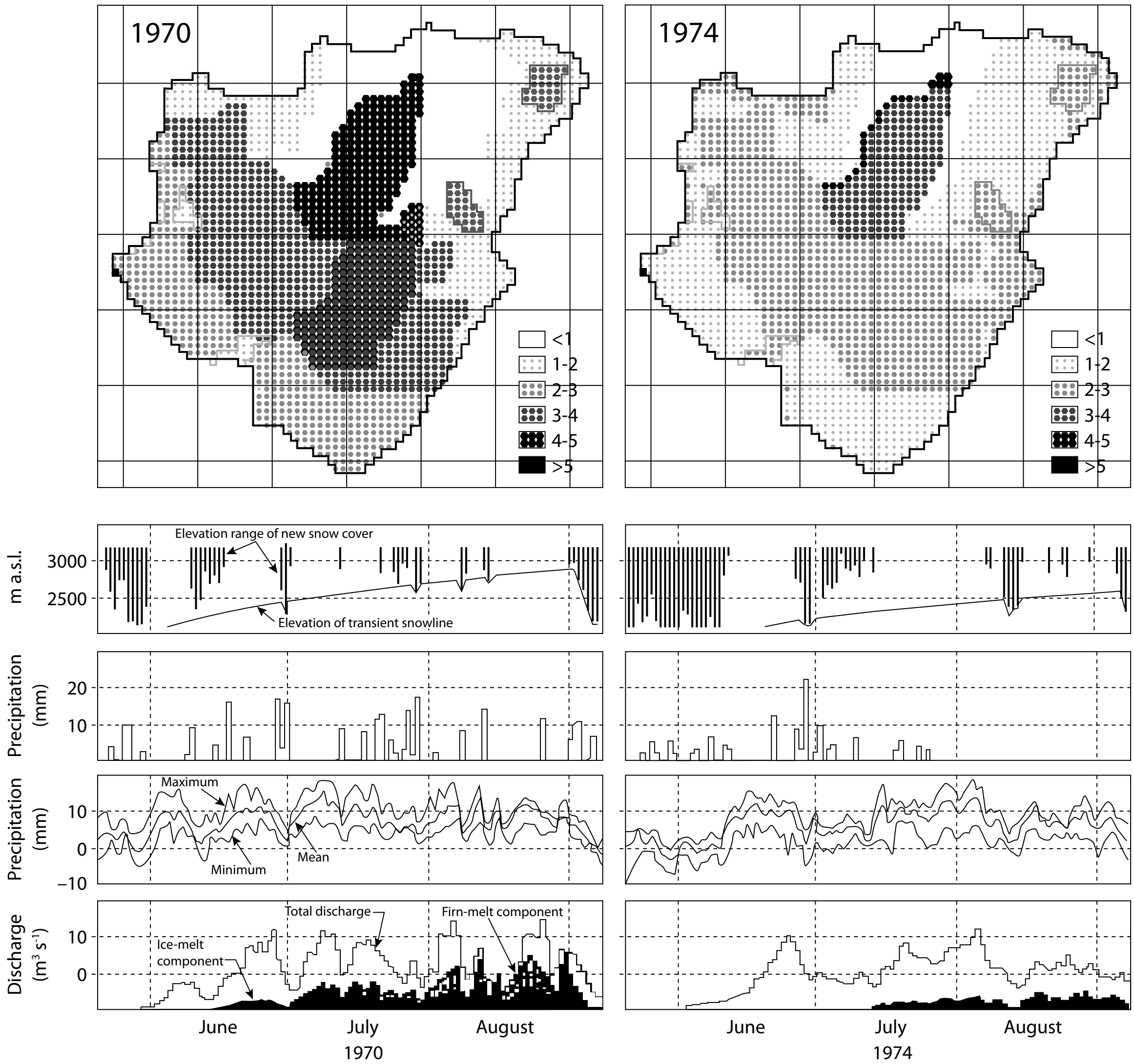


Figure 6 Peyto Glacier basin: Top: comparative maps of specific yield (m) for 1970 and 1974; Bottom: Snowline movement, meteorology and discharge relationships for 1970 and 1974 (after Young, 1982, 1990)

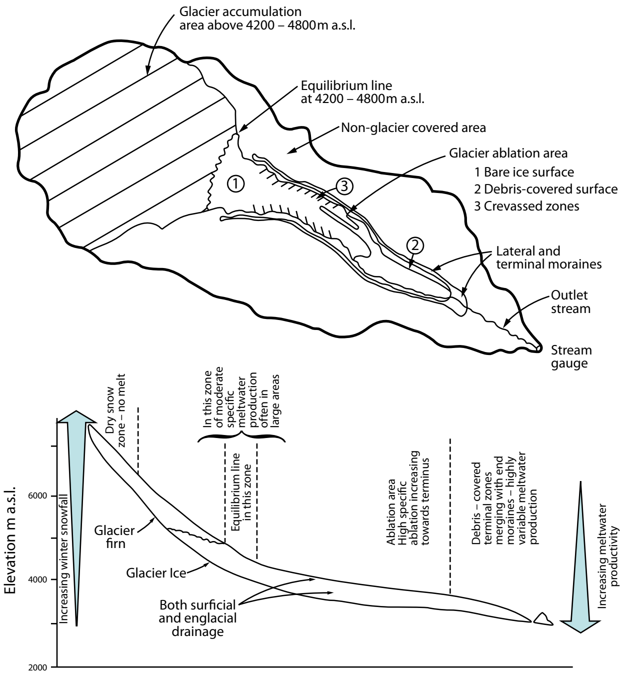
basin yield. Severskiy, I. (page 99) presents measurements made in the Tien Shan and particularly in the Tuyuksu Glacier region. He considers the relative contributions to runoff from melting glacier ice (glacier wastage), melting of dead glacier ice (in ice-cored moraines and dead glacier ice in the glacier fore-fields) and melting of permafrost.

Of this total ice melt he concludes that some 20% is derived from melting of dead glacier ice and permafrost with permafrost contributing only a small fraction of the total.

Glacier-related floods

Another element of high mountain hydrology is the occurrence of glacier-related floods. There are several types of such floods ranging from relatively simple snow and ice melt floods through glacier lake outburst floods (GLOFs) to outbursts of glacier-dammed lakes (jökulhlaups).

Heavy rainfall events can produce major flood events in almost any region of the world. In high mountain terrain with steep slopes and often with little vegetation to retain the water runoff can be



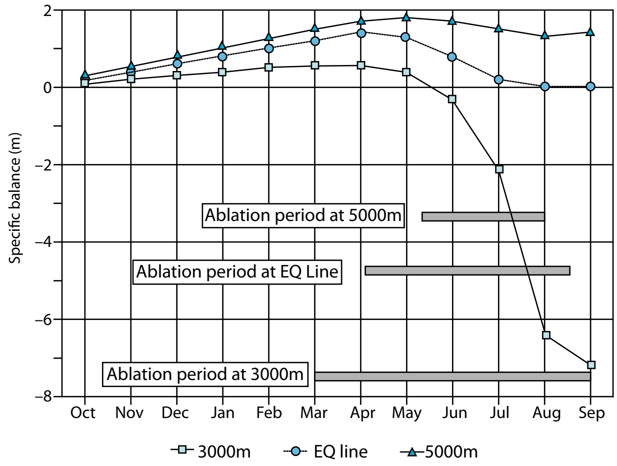


Figure 7 *Generalized specific yields within the different altitude zones of a large valley glacier within the Karakoram region (after Young and Hewitt, 1993). Note: these values should be taken as indicative only to illustrate the very different specific yields with elevation change.*

very fast. If such rainfall events occur late in the ablation season in glacier covered areas rainfall runoff can be compounded by both the contributions of melting ice and snow and by the fact that sub-glacier conduits are, by that time in the melt season, very well defined with the capacity to allow waters to pass very quickly.

Glacier lake outburst floods (GLOFs) are usually the result of small pro-glacial lakes emptying very rapidly producing a flood of very high intensity for very short duration. Small lakes are commonly formed at glacier termini being retained by lateral and end moraines. With glaciers retreating due to global warming such lakes are becoming larger.

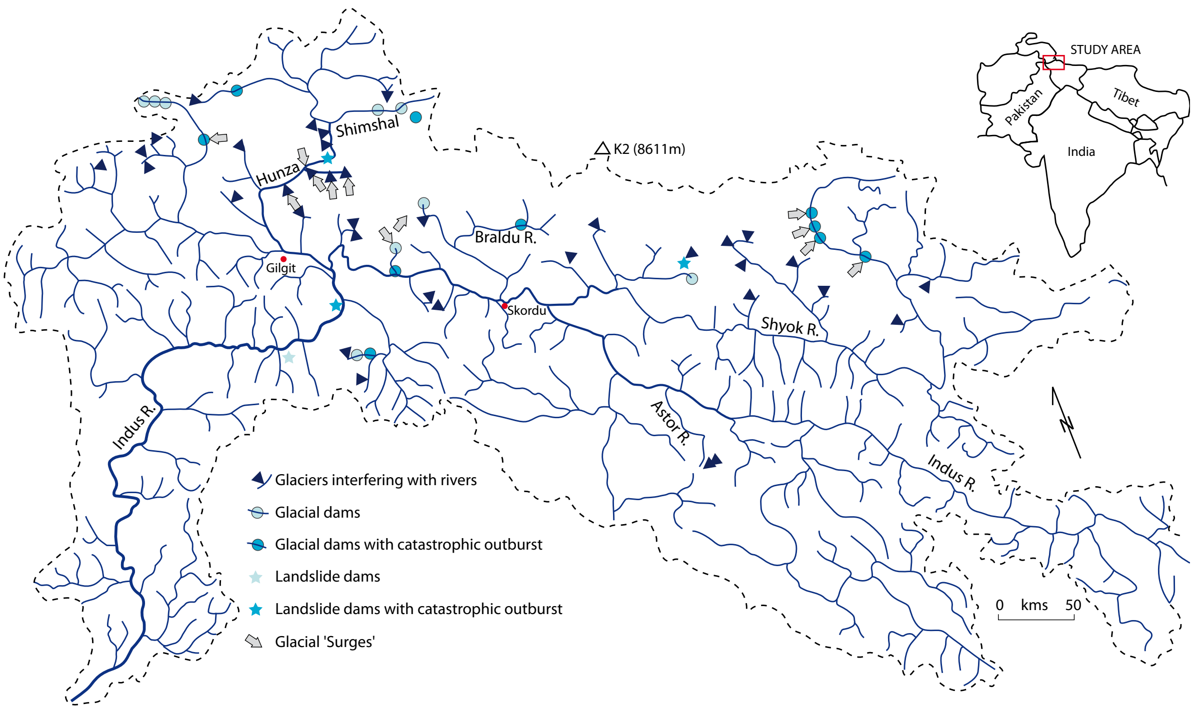


Figure 8 *Indus River: glacier dams and related events (after Hewitt, 1982)*

Sudden release can result from collapse of the retaining moraine or as a result of landslides falling into the lake with sudden displacement of much or all of the impounded waters. Good illustration of such floods in the Himalaya is given in the paper by Xu Jianchu, et al. (page 44).

Glacier outburst floods (jökulhlaups) occur in a number of situations but typically result from the sudden release of water from lakes impounded by glaciers that have dammed valleys. Particularly large lakes may be impounded when a major valley is blocked by advance of a glacier from a tributary valley. Release of lake waters may result either from over-topping of the dam or by sub-glacier drainage. Examples of such floods, which can be truly catastrophic, are given by Hewitt (1982) for the Karakoram and are illustrated in figure 8.

The physiography and hydrology of the Central Asian Region

General physiography

As shown in figure 1 many of the major mountain ranges of Central Asia radiate out from the Pamir massif on the borders of China, Tajikistan and Afghanistan. South and east of the Pamir runs the Karakoram range of northern Pakistan leading to the Greater Himalayan range which acts as a continuous barrier between China and India from Kashmir in the west to Assam in the east. North of the Karakoram and stretching in a great arc across northern Xizang (Tibet) run the Kunlun Shan. North from the Pamir runs the Tien Shan; the Central Tien Shan forming the border between China and Tajikistan and the Northern Tien Shan the border between Kyrgyzstan and Kazakhstan before branching east into Xinjiang. In central China there are several other notable ranges; the Nyainqentanglha Shan of south east Xizang blends into the Hengduan Shan of Yunnan Province. Further north there are several ranges the most notable of which is the Qilian Shan.

Climate

The whole area is characterized by extreme diversity of climate. The south eastern part of the region is dominated by the monsoon. Light winter precipitation contrasts with the torrential rains (snowstorms at higher altitudes) of summer. The deep river valleys of south eastern Xizang allow incursions of maritime air in summer into the Hengduan and Nyainqentanglha Shan. Glaciers provide meltwater during summer when temperatures are relatively high but the significance of the meltwater in the south eastern area is completely overshadowed by the monsoon precipitation.

Moving westward along the Himalaya the intensity of the monsoon 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 do receive heavy monsoonal summer storms which are the source of floods but the Karakoram proper is much less affected by the monsoon than the Himalaya. The Karakoram, Tien Shan and Kunlun receive much of their precipitation from winter storms coming from the Atlantic. The Qilian Shan, although away from the influence of the monsoon, has distinct summer maxima of precipitation.

Besides the seasonal contrasts in distribution of precipitation, total amounts vary 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 and Xinjiang Provinces of China.

The temperature regimes within the area are also a study in contrasts. The southern flanks of the Himalaya, almost always subject to tropical influences, rarely experience extreme cold. The Qinghai- Xizang Plateau, much of which is above 4000 m elevation and cut off from maritime influences by the Himalayan barrier, experiences extremely cold winters and cool summers (it is largely a permafrost area). The basins of the Takla Makan and Gobi deserts further to the north west are much lower in elevation (parts being below sea level) and they experience a markedly continental climate – very hot summers and very cold winters.

Local climates

Mountain ranges the world over are characterized by sudden changes in climate over very short horizontal 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 very marked in these mountain ranges of Central Asia where local relief can be extreme; an example of this is found in the Himalaya wherein the southern slopes can receive upwards of 4000 mm of precipitation annually while the northern slopes typically receive in the order of 200–300 mm.

Climate change

With rising global temperatures the cryo-hydrology of Central Asia is changing. Both permafrost and glacier covered areas are reducing in extent in many parts of the region. With higher temperatures a greater proportion of total precipitation falls 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 regimes of rivers and on subsequent human use of the waters.

Glacier cover

The main glacier-bearing ranges are the Himalaya, Karakoram, Kunlun, Tien Shan and Nyainqentaglha Shan, see table 4. The papers by Yao Tandong et al and Xin Li et al. (page 112) indicate that glaciers cover over 59,000 km^2 within China. The Karakoram, outside of China has in the order of 13,000 km^2 with a much higher density of glacier cover than the other ranges. The Himalaya, outside of China has in the order of 22,000 km^2. As of the mid 20th century about 37 % of the Karakoram was glacier covered, compared with about 17 % for the Himalaya (and about 2.2 % for the Alps). Further information on glacier extent and mass change are given in the papers by Finaev for Tajikistan (page 55), Glazyrin for Uzbekistan, Kuzmichenok for Kyrgyzstan, Narozhny et. al. for the Altai range and Severskiy, I for Kazakhstan and the Tien Shan in general. Also in the paper by Nakawo (page 19) additional information for Nepal and the Qilianshan is provided. The most comprehensive overall paper is given by Severskiy and Kotlyakov.

Ground ice

Vast areas within the high mountain ranges of central Asia are underlain by permafrost. These areas are particularly extensive in the Tibetan Plateau. The paper by Xin Li et. al. (page 112) states that there is about twice the volume of water stored as permafrost as is contained within glaciers; in the period 1975–2002 there was a shrinkage in volume of permafrost by about 12 %. However it is unclear what proportion of that shrinkage contributes to surface flows. Detail on the importance of the role of melting permafrost relative to melting of snow and glacier resources for the Tien Shan and especially for parts of Kyrgyzstan is given in the paper by Bolch and Marchenko (page 132).

River systems

Several of the largest rivers in the world have their headwaters in the Central Asian Region. The drainage system is complex and the rivers themselves vary greatly in volume and to a certain extent in regime. The Himalaya supports three major river systems, the Indus, Brahmaputra and the Ganges. The Indus, the Brahmaputra and many of the tributaries of the Ganges are examples of antecedent drainage; the river pattern predates the mountain formation and the rivers themselves rise on the north side of the mountains and break through them in a series of spectacular gorges.

Table 4 Surface areas of glaciers (After M.B. Dyurgerov and M.F. Meier, 2005)

Region	Area, km^2
Total in Europe	**17,290**
Total in Siberia	**3,500**
High mountain(HM) Asia	
Tien Shan	15,470
Dzhungaria	1,000
Tarbagatay	17
Pamir	12,260
Qilian Shan	1,930
Altun	266
Kunlun Shan	12,260
Karakoram	16,600
Qiantang Plateau	1,802
Tanggula	2,260
Gandishi	1,615
Niaingentanglha	7,536
Hengduan	1,618
Himalaya	33,050
Hindukush	3,200
Hinduradsh	2,700
Total in HM Asia	**116,180**
Middle East(Near East)	
East Caucasus(Caspian Sea basin)	781.7
Maliy Caucasus	3.8
Turkey	24
Iran	20
Total in Middle East	**830**
Total in Asia	**120,680**

Several of the very large rivers of south east Asia rise very close to each other in the eastern part of the Qinhai-Xizang Plateau. The Salween, Mekong and Yangtze flow roughly parallel and very close to each other through the Hengduan Range before taking their separate directions to the sea. The Huang He also rises in the same general area before flowing eastwards across northern China.

The Pamir and Tien Shan through the Syr Darya, the Amu Darya and the Ili support the internal drainage systems of the Aral Sea and Lake Balkhash, while the drainage of Xingjiang flows largely into centers of inland drainage in the deserts of Gobi and Takla Makan.

Total annual discharges vary greatly from the very high discharges of the Brahmaputra and Yangtze in the east to the desert rivers such as the Yarkand in the Tarim basin. While total flows vary there is a striking similarity in the seasonal regime of most of the rivers. Low flows in winter contrast with relatively very high flows in summer. The seasonal disparity in flows is the result of a combination of factors; but the relative importance of the factors differs from place to place. On almost all of the rivers spring snowmelt in the mountains in the months of April and May contributes significantly to streamflow. This is economically very important as many crops are planted in this period. In the summer months of June to September the rains in the Tien Shan and Qilian Shan and in the monsoon areas of the south east dominate the runoff. Floods at this time are made worse by the coincidental melting of the mountain snow and ice, although the contribution to flow of melting glacier ice is usually small. However, in the western Himalaya and Karakoram where the glaciers tend to be larger and summer rainfall is much less important the relative importance of glacier melt to streamflow is greatly increased.

It is generally the case that glaciers have a regulatory effect on streamflow. When annual snowfall is light glaciers tend to melt more, partially compensating for lower precipitation (to a degree depending on the proportion of the river basin covered by glaciers). Understanding the balance between the different components of discharge can be important in making decisions on when to fill or empty reservoirs.

Major conclusions from the workshop

- Climate change is taking place in the Central Asian region. There is strong evidence of gradual but persistent warming. However there is little evidence for major changes in snowfall and precipitation in the high mountain regions. There may well be significant losses of water due to increased evaporation especially in the lower reaches of the major rivers, but this issue was not specifically dealt with by the papers.
- The warming is resulting in shrinkage of glaciers and the melting of ground ice both in the form of permafrost and dead glacier ice. This water coming out of permanent storage may account for some 4 to 6 % of total annual flows on the rivers as they emanate from the mountain zones. This is a small but very significant percentage. For the next few decades this contribution to total flows is likely to persist and in some areas the percentage may slightly increase. In the longer term (some 50 to 100 years) as ice masses both on the surface and underground decrease in volume their contribution to total flows will likely diminish.
- While total annual flows are likely to remain about constant on average for the next few decades, flow regimes are likely to change; interannual variability in flows will likely increase and reliability of flows in the late summer period will likely decrease due to the lowering of the buffering effect of glacier melt.
- There should be a strong plea for resumption of monitoring at high elevation in the Amu Darya, Syr Daria and Ili drainages.

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Shrinkage of summer-accumulation – glaciers in Asia under consideration of downstream population

M. Nakawo

A rapid shrinkage of glaciers in the Nepal Himalayas has occurred in the last 25 years, despite the fact that the rise in air temperatures has not been as pronounced as the global average. One of the most important reasons for this shrinkage is that snow accumulates in summer and not in winter. Glaciers in the Qilian Mountains, western China, are also fed during summer, and they have deteriorated rapidly as well. Because of this glacier shrinkage, the rate of river discharge has increased slightly and yet people in the river basin have suffered from a water shortage, which is thought to be the result of human activities. Glaciers are an important water resource, in particular in the arid and semi-arid regions of central Eurasia. Glacier studies, therefore, should be combined with studies of social systems and of human culture, taking into account their proactive and reactive effects.

Glaciers shrinkage in the Nepal Himalayas

Retreat of glacier termini
Photos 1 and 2 are photographs of Rikha Samba Glacier, central Nepal, and AX010 Glacier, eastern Nepal, respectively, showing the rapid retreat of these glaciers in the last 20 to 25 years. In case of the Rikha Samba Glacier, the rate of retreat has been about one meter per year (Fujita et al., 1997).

Comparing maps compiled from airborne imagery taken in 1958 and 1992, Asahi (2001) reported aerial changes of every glacier in eastern Nepal, and mapped the distribution of advanced, stationary, and retreating glaciers. In the Khumbu Region, for example, the area of most small glaciers decreased, while a small number of these small glaciers advanced.

Photo 1 *Retreat of the terminus of Rikha Samba Glacier, Hidden Valley, Nepal (Pictures taken by Glaciological Expedition of Nepal, and Cryoshere Research in the Himalayas)*

Photo 2 *Retreat of the terminus of the AX010 Glacier, Shorong Himal, Nepal Pictures taken by Glaciological Expedition of Nepal, and Cryoshere Research in the Himalayas)*

Large glaciers, whose ablation area is mostly covered with debris, showed no changes in extent. However, they have experienced a loss in ice mass, as their thickness has decreased. This matter will be discussed below.

Change of glacier volume
Three glaciers were examined with regard to changes in their volume. Rikha Samba Glacier lost 548.8 x 10^5 m^3 of ice during the period from 1974 to 1994. The volumetric difference of Glacier AX010 was 10.4 x 10^5 m^3 between 1978 and 1999, and Yala Glacier lost 9.3 x 10^5 m^3 from 1982 to 1996. When expressed in terms of the thinning rate over the whole glacier, the surface lowering amounted to 0.55 m/year on Rikha Samba Glacier, 0.72 m/a on Glacier AX010, and 0.36 m/year on Yala Glacier.

Figure 1 compares these thinning rates with mass balances of glaciers in other parts of the world. On the x-axis, annual mass balance amplitude is expressed, since the mass balance of glaciers with large amplitudes react stronger than those with small amplitudes (Meier, 1984). It can be concluded from the figure that Himalayan glaciers have lost mass at a faster rate than glaciers with the same amplitude in other regions.

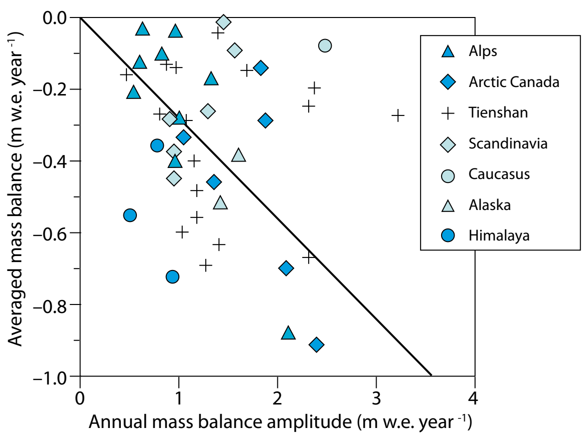

Figure 1 *Rates of glacier thinning in various parts of the world (Fujita* et al., *1997). For a given annual mass balance amplitude, Himalayan glaciers have lost mass at a faster rate than glaciers in other regions.*

Supraglacial moraine

In the Nepal Himalayas, the ablation areas of large glaciers are usually covered with debris. Ice mass under this debris was considered stagnant, because thick debris on the surface was thought to play the role of an insulator, and ice melt below was considered negligible. Repeated surveys have indicated, however, that the glacial thickness has decreased at a rate of about one meter per year in the case of the Khumbu Glacier, one of the debris-covered glaciers in the Khumbu Region. A similar rate of thinning was observed on the Lirung Glacier, another debris-covered glacier in Langtang Khola, central Nepal.

It is difficult, in the case of such debris-covered glaciers, to estimate the average thinning rate for the whole glacier, because less information is available with regard to the accumulation area of debris-covered glaciers, which tend to be located at very high altitudes. The significant thinning in their ablation area, however, indicates that debris-covered glaciers also have lost their mass at a high rate, although the exact rate has yet to be assessed.

It can be stated, that over the last few decades glaciers have deteriorated rapidly in the Nepal Himalayas. This shrinkage may have been caused by recent global warming, but careful investigations will be necessary before a firm conclusion can be reached.

Recent warming in Nepal

Instrumental data

In the previous chapter, we showed that the rate of glacier shrinkage has been significant in the Nepal Himalayas. Does this mean that there has been a similarly significant rise in air temperatures?

Figure 2 shows daily maximum air temperature data, averaged for all of Nepal, taken from rural observation sites only, and discarding temperatures recorded at city sites, where heat island effects may have occurred. The record shows an increase after 1970, as shown by the dotted line. The rate of temperature rise seems to have increased after 1980, as shown by the solid line.

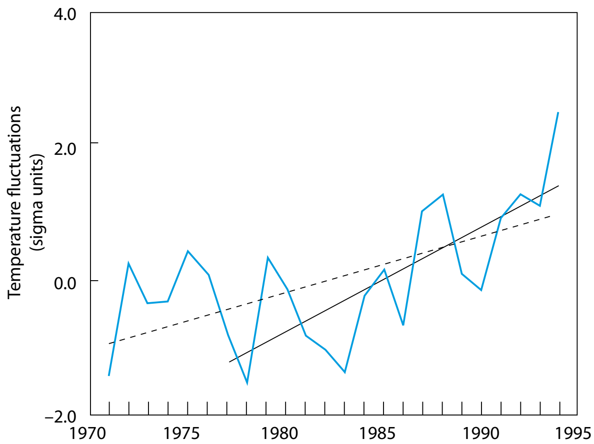

Figure 2 *Average temperature data at 49 rural observation sites in Nepal, after 1970 (Shrestha* et al., *1999).*

Proxy data

Temperature data is generally collected at low elevations where most observation sites are located. In the mountains, at the altitude of glaciers, the temperature rise may be more pronounced. Since no instrumental data are available, proxy data must be referred to.

The stable isotope content of ice cores retrieved at Rikha Samba Glacier decreased slightly from 1960 to 1980, and increased slightly during the period from 1980 to 2000. This may indicate that the temperature increase at the glacier was not as rapid as the global average. In the Himalayas, however, it has been debated whether measurements of isotope content in ice cores can serve as a proxy for temperature, since the isotope content of falling snow is higher in spring than in summer.

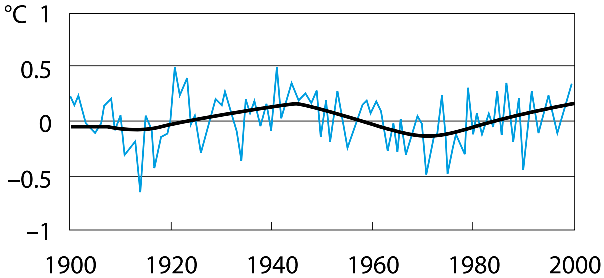

Figure 3 *Change of summer air temperature anomalies (°C), reconstructed by dendrochronology.*

Figure 3 shows summer temperature anomalies based on reconstructed summer temperatures derived from an analysis of tree-ring samples taken at about 4000 meters above sea level in western Nepal (Sano et al., 2005). This analysis also revealed a temperature rise of about 0.1 °C/10 years after 1970, but, the rate of increase was not as pronounced as it was for the global average air temperature of about 0.2 to 0.3 °C/10 years (IPCC, 2001).

Cook et al. (2003) compiled data based upon tree-ring analyses carried out in Nepal. They also showed a warming trend into the late-20th century, but only in winter. In summer, the temperature seems to have even decreased, suggesting that warming was not pronounced in Nepal.

Although temperatures have increased in Nepal, rate of the warming is by no means large enough to explain the rapid shrinkage of the glaciers.

The cause of the rapid shrinkage of Glaciers

Summer Accumulation

Figure 4 shows seasonal changes in air temperature and precipitation observed at the Rikha Samba Glacier, at an elevation of more than 5000 m. Precipitation occurs mostly from June to September, during the summer monsoon season. During summer, when this precipitation occurs, air temperatures are a few degrees above freezing. For the remainder of the year, air temperatures generally remain below the freezing point.

It was observed, in the Nepal Himalayas, that precipitation is in a solid phase when the air temperature is above 1 °C , and in a liquid phase when air temperatures are above 4 °C (Ageta et al., 1980; Ueno et al., 1994).

Looking at the temperature record shown in figure 4, it appears that snow accumulation on glaciers generally takes place during the monsoon season (“summer-accumulation type glaciers” after Ageta and Higuchi 1984). The air temperature during this period, therefore, is very critical, as it determines the aggregational state of precipitation. When the air temperature rises slightly, solid precipitation becomes liquid and the amount of accumulation decreases significantly. In other words, the amount of annual accumulation, on Himalayan glaciers, is very vulnerable to warming.

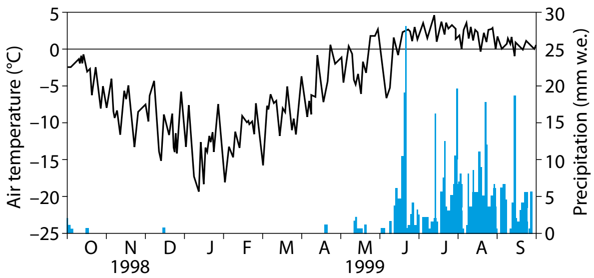

Figure 4 *Seasonal variations in air temperature and precipitation at the Rikha Samba Glacier, central Nepal, October 1998 to September 1999 (Fujita* et al. *2001).*

Because the major accumulation season is in the summer, Himalayan glaciers are often covered with new snow during the summer months. The summer, however, is also a major ablation season for glaciers. Frequent snow cover, in particular in the ablation area, would hinder the ablation of glaciers due to the high albedo of new snow. Warming in the Himalayas, therefore, would lead to less frequent snow cover, and as a result, ablation is accelerated. This is the “albedo effect”, resulting from warming of the atmosphere.

Warming would certainly accelerate the ablation of glaciers, even without this albedo effect. Himalayan glaciers are, hence, very vulnerable to warming, because of the combination of three causes: a decrease of accumulation due to the phase change of precipitation, the albedo effect’s acceleration of ablation, and accelerated ablation due to an increase of sensible heat fluxes.

Glaciers in other parts of the world are mostly fed during winter. With warming temperatures, their ablation increases, but the other two causes for the shrinkage of Himalayan glaciers, would not affect their mass balance, because accumulation takes place in winter.

Therefore, it is concluded that the rapid shrinkage of Himalayan glaciers, even given a mild warming trend, results primarily from the fact that glaciers are fed during the summer: accumulation and ablation take place simultaneously and both are affected towards a more negative mass balance.

Photo 3
Yala Glacier, covered with black biological matter.

Biological activities
Photo 3 is a photograph of Yala Glacier, central Nepal, taken in summer 1994. The glacier surface is dark, almost black. The black material was found to be micro biological communities, such as green algae and cyanobacteria, as shown in Photo 4.

Photo 4
Microphotograph of cyanobacteria

An abundance of these organisms results in a low surface albedo and accelerates ablation. The quantities of this material are several times greater for Himalayan and Tibetan glaciers than it is for Patagonian, Alaskan, and Arctic glaciers (Takeuchi et al., 2006). It remains unclear why this growth is typical for Asia. This biological material, however, may have led to a more rapid shrinkage of glaciers in the Himalayas than of glaciers in other regions, although we are not sure whether the biological activities are only a recent phenomenon.

Water shortages in the Heihe Basin, Western Cina

Stable river flow in a warming climate
The rapid shrinkage of glaciers in the Himalayas has been reported above, and the major cause of this is seen in summer accumulation. Glaciers in western China are also of the summer-accumulation type and therefore can be expected to have shrunk at a high rate as well.

We have examined the 7–1 Glacier in the Qilian Mountains. The terminus has retreated by about 100 to 140 meters in the last 25 years, at an average of 4 m/year. The glacier has lost approximately one tenth of its mass in the same period. This was determined through a comparison of our recent observation data and a glacier map prepared by the Lanzhou Institute of Glaciology and Geocryology in 1975. The rate of mass loss is consistent with an average rate of thinning of about 0.3 m/year for the whole glacier (Sakai et al. 2006). The rate is not as rapid as it is for the Himalayan glaciers, but considering that both accumulation and ablation are not very large on this stronglycontinental glacier, the retreat is significantly high.

At Zhangye, one of the closest cities to the glacier, a gradual increase in air temperatures has been observed, at a rate of about 0.5 °C over the last 50 years. Stable isotope content in an ice core from Qilian Mountains indicates a recent temperature rise also in the mountains and this warming may serve to explain the deglaciation.

Glacier devastation leads to an increased river discharge since thinning glaciers supply additional water to stream flow.

Precipitation appears to have increased at Zhangye. At high elevations, however, it seems to have decreased slightly, when precipitation in the mountains is estimated from an ice core.

While warming may have caused a decrease in precipitation, as reported at several sites in arid and semi-arid regions, the increase in glacier melt would, to some extent, compensate this loss. There are data to suggest that the volume of runoff flowing from mountains to the middle reaches of the river, where communities make use of irrigation agriculture, has not changed over the past 50 years. In fact, if anything, runoff has increased only slightly (Figure 5).

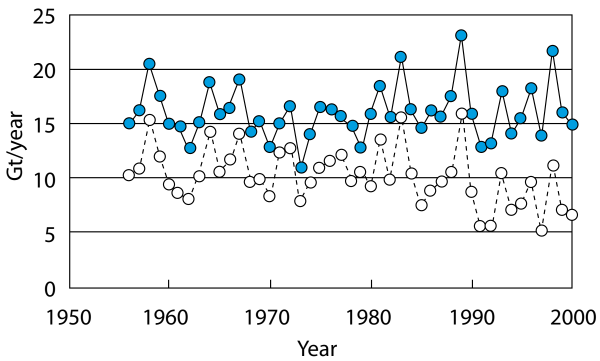

Figure 5 *River discharge of the Heihe River. The solid line indicates discharge from the mountains to the middle reaches, measured at Yingluoxia (1674 m a.s.l.) and the dotted line with an open circle shows the discharge from the middle reaches to the lower reaches measured at Zhengyixia (1280 m a.s.l.) (y-axis is in Gt/year).*

The Heihe River is a typical inland river. It originates in the Qilian Mountains at the border of the Qinghai and Gansu provinces in western China, and flows north before finally emptying into a couple of inland lakes in the Inner Mongolian Autonomous Region. After Tarim River, Heihe is the second largest inland river in China, with a basin area of approximately 130,000 km².

In the Heihe River Basin, annual precipitation ranges from 200 to 800 mm in the mountains, while it is only about 100 mm in the lowlands where most people are living. These communities strongly depend on water coming from the mountains, including the melt water from glaciers. It is of great importance, therefore, to have a stable river discharge from the mountains. As we have described above, the discharge from the mountains is generally stable as the climate warms, and people do not appear to be suffering from the effects of climate change.

Water shortages and measures taken
Although annual discharge from the mountains has not changed significantly, various symptoms of water shortage have appeared, particularly in the lower reaches. Examples of this include falling water levels in wells, forcing people to dig new, deeper wells in order to secure water, a decline in natural riparian vegetation, reductions in forested areas, and substantial deterioration in the condition of grasslands surrounding these forests. In addition, two lakes into which the Heihe River once flowed have disappeared, the first in 1961 and the second in 1992.

Figure 5 also shows the river discharge from the middle reaches to the lower reaches where water shortages have been remarkable. As can be seen, the discharge to the lower reaches decreased from around 12 Gt/year in the 1950s to about 8 Gt/year in 2000, a decrease of roughly one third in half a century. The difference between the discharge from the mountains and the amount of water to reach the lower reaches can be accounted for by the amount of water consumed in the middle reaches, where vast areas are irrigated for agriculture. Water consumption has more than doubled during this period, from 4 Gt/year to 9 Gt/year (Hidaka and Nakawo, 2006). The area of irrigated land also increased sharply. It was three times larger in 2000 than it was in the 1950s (Wang and Cheng, 1999).

A couple of measures have been adopted in response to this water shortage. First, the presence of forests in the mountainous region is thought to be important to stable river flow from the mountains to the lowland areas. Animals raised and kept by pastoral people are considered to damage the mountain forest by eating the young leaves of trees. It was recommended, therefore, that the pastoral people, together with their animals, relocate to the lowland areas, where they could either become agricultural farmers or continue to keep livestock, but in barns. This was called the "Ecological Relocation Policy" (Konagaya et al., 2005).

In the middle reaches, some Yugu people, an ethnic minority, have kept their animals on a limited area of grassland. Because of recent grassland deterioration, they have been encouraged to relocate to a "model village" where houses and barns have been provided for agricultural activities and the keeping of livestock.

In the lower reaches as well, pastoral Mongols have been asked to relocate either to an oasis in the desert zone or an area in the desert away from the river, because it is thought that their animals have been causing damage to the riverside forests.

Let us now consider the results of this "Ecological Migration" policy.

Some of the pastoral people who relocated to new sites in the middle reaches became farmers, who, however, required water for their farming activities. Water use from the river is strictly limited, partly by regulation and partly by water rights that those who relocate do not have access to. They turned then to the use of groundwater, whenever possible. This accelerated groundwater consumption because the original farmers had also become more dependent on ground water.

Some immigrants still keep their animals in barns at the new site. They are required, however, to feed their livestock with grass they have planted, whereas before they had made use of natural grasses. For this grass cultivation, they certainly require water, as do those immigrants who became farmers.

As a result, the amount of water consumed in the middle reaches increased rapidly, by about 6 times, during the 20 years from 1980 to 2000.

In the lower reaches, we can find similar changes among those who were relocated to the oasis. They too require additional water for farming, and this is taken from groundwater. People that have relocated to desert areas, away from the river, also require water for their animals and for daily life. Although the grass grown to feed livestock is fed by natural precipitation, they have also dug new wells.

In any case, the consumption of groundwater has increased rapidly, leading to a significant lowering of the groundwater level, and "Ecological Relocation" is partly responsible for this overuse of groundwater. Stable isotope analysis of groundwater from the Heihe River Basin indicated that it had formed over a period of hundreds of years. Groundwater is extremely important. It should be used in a sustainable way and not be consumed by one generation. Thus, a water resources management has to be established, taking into account groundwater as well.

"Ecological Relocation" was undertaken primarily to restore and/or to maintain a good ecological condition by overcoming the water shortage. Another incentive for this migration policy, however, has been an improvement in the economic condition of migrants, helping them to escape from poverty. Relocated pastoral people, however, have to spend additional money for the excavation of deep wells, since shallow wells are no longer practical. The details of their economic condition are beyond the scope of this paper, but "Ecological Relocation" in the Heihe Basin does not seem to have been successful in this respect either. In fact, "Ecological Relocation" appears to have resulted in a deterioration of the culture of the migrants, although this is beyond the scope of this paper as well.

Summary

In the Himalayas, recent warming has by no means been very rapid, and it is thought to be a rebound from the little ice age. It is rather gentle, when compared with the average rate of temperature rise for the northern hemisphere. Despite this, glaciers in the Himalayas have shrunk at a marked rate.
As shown above, the rapid shrinkage of glaciers is mainly caused by the fact that glaciers are fed during the summer months, when also accumulation is at its maximum.

Glaciers in the Qilian Mountains in western China, which are also fed during the summer, have suffered a loss of mass at a significant rate as well. This shrinkage has supplied additional water to the rivers, offsetting a decrease in precipitation. As a result, the rivers have maintained stable levels even as the climate has warmed.

River water from the mountains is very important in the arid and semi-arid regions of central Eurasia and people strongly depend on stream flow from the mountains. Due to the large fraction of glacier melt in central Eurasian rivers, it is of great importance to monitor glacier changes in keeping with global warming. For example, the contribution of glacial melt water to the total river discharge was found to be roughly half for the Yurungkax and Keriya rivers flowing from the Kunlun Mountains to the Taklamakan Desert (Figure 6).

However, water shortage is a major issue in the Heihe River Basin, even though discharge from the mountains is generally stable. This suggests that we must take into account how water is distributed, or shared, by different groups of people, i.e. human activities.

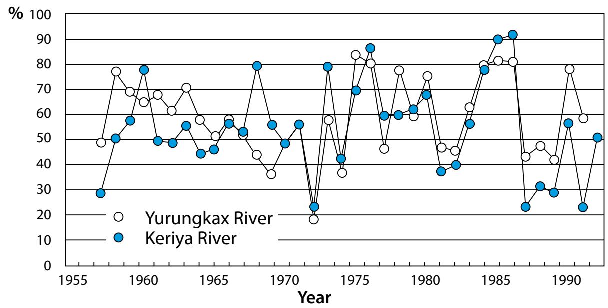

Figure 6 *Contribution of glacial melt water to the total river discharge for two rivers in the Kunlun Mountains (Ujihashi & Kodera, 2000)*

We have also seen that one of the measures for solving the water shortage, namely "Ecological Relocation," has not been effective. In fact, the outcome appeared to be completely different from what was intended.

It should be stressed, therefore, that glaciological and/or hydrological studies should be combined with social and human studies. To overcome global environmental problems, integrated studies are essential, as we have seen in the case study of the Heihe River Basin.

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Recent glacial retreat in the Chinese part of High Asia and its impact on water resources of Northwest China

Yao Tandong, Wang Youqing, Liu Shiying, Pu Jianchen, Shen Yongping and Lu Anxin

Under the impact of climatic warming, the glaciers in the Chinese part of High Asia have been experiencing a negative glacial mass balance and have been retreating continuously over in the most recent decades. The retreat became more intensive in the past 10 years. The spatial pattern of the glacial retreat in the Chinese part of High Asia can be summarized as follows: The smallest retreat rates are located in the inland of the Tibetan Plateau. The rates increase from the inland to the margins of the Tibetan Plateau with the highest rates being observed at the margins of the Tibetan Plateau. The glacial retreat in the Chinese part of High Asia has an important impact on the water resources of the arid regions of Northwest China. This study shows that the glacial retreat in the 1990s has caused an increase of 5.5 % in river runoff in Northwest China. In the Tarim River basin, the increase of river runoff is even higher than that.

Introduction

There are 46298 glaciers in the Chinese part of High Asia with a total glacial area of 59406 km^2 and a total glacial volume of 5590 km^3. The glaciers are mainly concentrated around the Himalayan Mountains, Nyainqêntanglha Mountains, Kunlun Mountains, Karakoram Mountains, and Tianshan Mountains. The glaciers of the Tibetan Plateau are the major component of the glaciers in the Chinese part of High Asia. The glaciation extends north to the arid and desert regions and is the main water resource in Northwest China. Especially, the large glacier coverage around the Tarim Basin can supply $137.7 \times 10^8 m^3$ of glacial melt water to the lower reaches of the Tarim Basin each summer. There are also glaciers to the South in a region characterized by warm, wet forests mainly concentrated around the Brahmaputra Drainage Basin. There are 10813 glaciers in the Brahmaputra Drainage Basin with a total glacial area of 14491 km^2 and a glacial volume of 1293 km^3.

Glaciers fluctuate with climatic change. The numbers mentioned above are mainly based on data obtained in the 1970s or 1980s contained in the *Glacier Inventory of China*. In the 1980s, most of the glaciers were retreating intensively because of climatic warming. Even some previously advancing glaciers had shifted into a state of retreat with rapid climatic warming. In the 1990s, the glaciers retreated more intensively, and the runoff of some rivers increased considerably due to the contribution of glacial melt water (Shi Yafeng, 2001).

Glacial retreat in the chinese part of high Asia

The changes of the glaciers in the Chinese part of High Asia can be divided into several stages as follows: The first stage was the first half of the 20th century when most glaciers advanced or shifted from advance to retreat. The second stage was the 1950s and 1960s when many glacial observations had started and, according to the data presented in table 1, the glaciers in the Chinese part of High Asia had begun to retreat intensively. According to previous studies (Zhang Xiangsong et al., 1981; Ren Binghui, 1988; Shi Yafeng et al., 2001, 2002), about two thirds of the glaciers were retreating while only 10 % were advancing with some glaciers remaining stable without any significant advancing or retreating. The third stage was between the late 1960s and the 1970s

Table 1 Proportions of advancing and retreating glaciers in the Chinese part of High Asia in different time periods

Time	Glaciers	Retreating Glaciers (%)	Advancing Glaciers (%)	Stable Glaciers (%)	Reference
1950 – 1970	116	53.44	30.17	16.37	Zhang Xiangsong *et al.*, 1981; Ren Binghui, 1988
1970 – 1980	224	44.2	26.3	29.5	Zhang Xiangsong *et al.*, 1981; Ren Binghui, 1988
1980 – 1990	612	90	10	0	Yao Tandong *et al.*, 1988; this paper
1990 to now	612	95	5	0	this paper

when the glacial mass balances were positive, the snowline dropped and many glaciers advanced. The fourth stage was during the 1980s when glaciers retreated intensively again. The fifth stage, the 1990s, can be characterized by the most intensive glacial retreat compared to any other period in the 20th century.

The glaciological expedition in the Tibetan Plateau in 1989 revealed that the glaciers of the southeast Tibetan Plateau retreated intensively with the Zepu and Kaqing Glacier showing the most intensive glacial retreat (Yao Tandong et al., 1991). But some glaciers were still advancing. Detailed research of the Large Dongkemadi Glacier and the Small Dongkemadi Glacier in the Tanggula Mountains and the Meikuang Glacier in the Kunlun Mountains showed that these glaciers were still advancing during those years. However, all these glaciers have subsequently shifted from advance to retreat during the 1990s. Presently, the glaciers in the Chinese part of High Asia are generally retreating except for very few glaciers that are still advancing.

The glacial retreat since the 1990s has several main features as described in the following: First, the magnitude of glacial retreat is increasing. The Glacier No.1 in the Urumqi River Basin in the Tianshan Mountains is an example of this. Glacier No.1 consists of two branches (east and west). The ice tongues of both branches joined together in 1962, but the joined part was thinning continuously with the retreat of the two branches. In 1993, the two branches were totally separated from each other and the distance between the two branches reached more than 100 m in 2001. Figure 1 shows the retreat of Glacier No.1 between the 1960s and 2000. Glacier No.1 retreated intensively from the early 1960s to the early 1970s at a retreat rate of 6 m/a. The magnitude of glacial retreat decreased considerably during the mid-1970s and reached a minimum in the early 1980s, but increased again during the late 1980s to the 1990s with the retreat rate reaching a maximum of 6.5 m/a between 1990 and 1991.

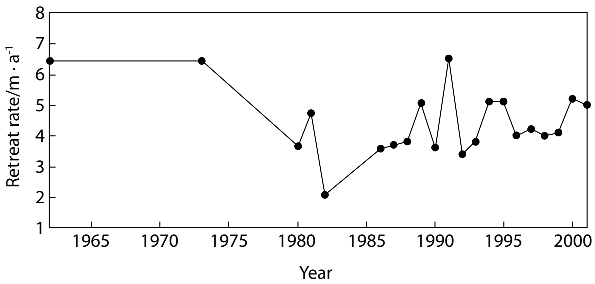

***Figure 1** Fluctuation of Glacier No.1 in the Urumqi River Basin*

Second, most of the advancing glaciers gradually shifted to retreat. The Large and Small Dongkemadi Glaciers in the Tanggula Mountains are examples of this as illustrated in figures 2 (a) and (b). These two glaciers were both advancing when they were first observed in 1991. The total area of the Large Dongkemadi Glacier was 14.63 km^2, while the area of the Small Dongkemadi Glacier was 1.77 km^2. According to glaciology, there is a lag-time of glacier response to climatic change. The lag-time is dependent on glacial size: the larger the glacier, the longer the lag-time. Consequently, the point in time when the Small Dongkemadi Glacier began to shift from advance to retreat should have been earlier than that of the Large Dongkemadi Glacier. As shown in figure 2 (b), the Small Dongkemadi Glacier advanced about 4 m during the summer of 1992 and then shifted to retreat in 1993 with a retreat rate of 0.2 m/a for that year. After 1993, the Small Dongkemadi Glacier kept retreating and the retreat rate increased year by year reaching 2.86 m/a in 2000.

The Large Dongkemadi Glacier advanced about 15.7 m between 1989 and early 1994, and then shifted to retreat after the summer of 1994. The annual retreat rate of the Large Dongkemadi Glacier also increased continuously and the retreat rate reached about 4.56 m/a in 2001.

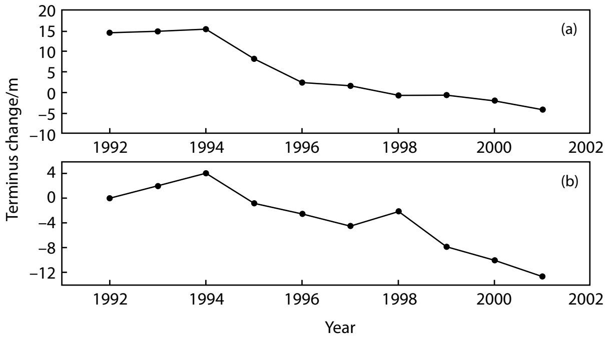

Figure 2 *Fluctuations of the Large Dongkemadi Glacier (a) and the Small Dongkemadi Glacier (b) in the Tanggula Mountains*

The impact of global warming on the glacial process can be seen at the highest peak of Mt. Qomolangma. According to Ren Jiawen et al. (1991), climatic warming caused glacial retreat in Mt. Qomolangma. According to the observations of Chen Junyong et al. (1998), the height of Mt. Qomolangma has dropped since 1966. The observation data show the dropping process of the height of Mt. Qomolangma in the past several decades. As shown in figure 3 (a), the height of Mt. Qomolangma decreased by a total of 1.3 m (from 8849.75 m to 8848.45 m) between 1966 and 1999. The annual fluctuations of the height of Mt. Qomolangma (Figure 3 b) are as follows: the height declined very rapidly between 1966 and 1975 at an annual of about 0.1 m/a; the dropping process slowed between 1975 and 1992 to a rate of only about 0.01 m/a, one tenth of that between 1966 and 1975, and then increased again between 1992 and 1998 to a rate of 0.1 m/a. The decline reached a maximum rate of 0.13 m/a between 1998 and 1999. Such a large drop of elevation in such a short time confirms that the elevation decrease cannot be attributed to the movement of lithosphere but can only be explained by the response of the glacier to climatic change. Strictly speaking, no glacial retreat can cause the glacial surface height drop at 8848 m a.s.l. but the reduced formation of glacial ice can induce the glacial surface height drop. The depth of snow and ice at the top of Mt. Qomolangma is still unclear. The highest reported depth was 2.5 m as observed by an Italian mountaineering team using a stick. But the true depth of snow and ice cannot be confirmed with this method. However, the snow and ice depth at the top of Mt. Qomolangma should be deeper than 2.5 m. Before global warming, the snow-ice processes at this altitude were characterized by a very slow densification under gravity similar to that in Antarctic and Arctic regions. The snow-ice formation process will accelerate due to increased temperatures as a result of global warming, which will cause the glacial surface height to drop rapidly. In fact, the height decline period at the top of Mt. Qomolangma since 1992 corresponds closely to a period of rapid climatic warming.

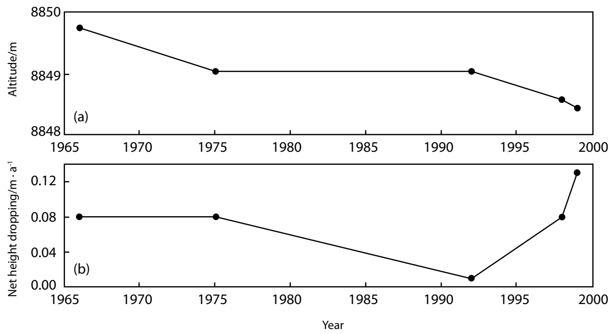

Figure 3 *Height fluctuations at the top of Mt. Qomolangma. (a) absolute elevation values and (b) the rates of decline in different periods*

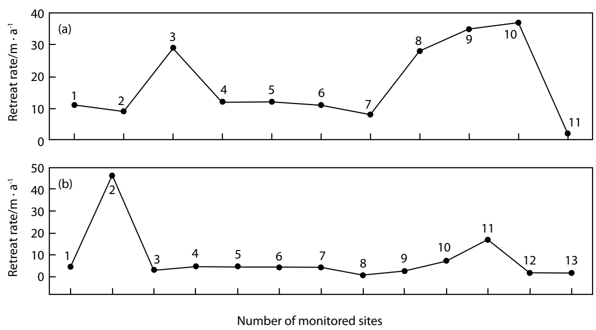

Figure 4 *Regional features of glacial retreat in the Chinese part of High Asia. (a) The annual retreat rate of all the glaciers in a region: 1, Altai Mt.; 2, Tian-shan Mt.; 3, Karokoram Mt.; 4, Qilian Mt.; 5, Himalaya Mt.; 6, Tanggula Mt.; 7, Gangdes Mt.; 8, Kunlun Mt.; 9, Nyainqêntanglha Mt.; 10, Hengduan Mt.; 11, Qiangtang Plateau. (b) The annual retreat rate of glacial length observed in different regions: 1, Glacier No. 1; 2, Pasu Glacier; 3, Qiyi Glacier; 4, Xidatan Glacier; 5, Dasuopu Glacier; 6, Kangwure Glacier; 7, Qiangyong Glacier; 8, Larger Dongkemadi Glacier; 9, Small Dongkemadi Glacier; 10, Rongbuk Glacier; 11, Hailuogou Glacier; 12, Puruogangri Glacier; 13, Malan Glacier.*

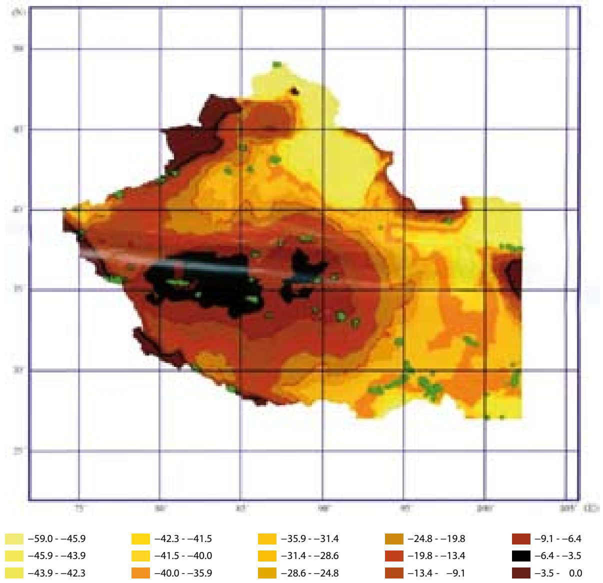

***Figure 5** Regional features of the glacial fluctuations in the Chinese part of High Asia*

The rate of glacial retreat is different in different regions according to numerous studies (Chen Jiaming et al., 1996; Su Zheng et al., 1996, 1999; Li Shiyin et al., 2000, 2002; Pu Jianchen et al., 2001; Wang Zongtai et al., 2001; Jing Zhefan et al., 2002; Lu Anxin et al., 2002). Figure 4 (a) shows the actual retreat rates of typical glaciers in different regions according to observations. These observations indicate that glacial retreat was intensive in the Karakorum Mountains and the Southeast Tibetan Plateau (Figure 4 (b)) with the annual retreat rate of the Poshu Glacier in the Karakorum Mountains reaching about 50 m/a. Overall, the annual glacial retreat rate in the Karakorum Mountains reached on average about 30 m/a, while 40 m/a were obtained for the Southeast Tibetan Plateau. Generally, within the plateau the magnitude of glacial retreat is smaller in the inland and larger at the margins. Glacial retreat rates for the inland plateau were typically less than 10 m/a. For example, the annual retreat rate of the Puruogangri Glacier and the Malan Ice Cap in the Tibetan Plateau was under 10 m/a. The same values were found for the Kunlun and Tanggula Mountains located in the central Tibetan Plateau. The regional differences of glacial retreat result in an elliptical pattern of glacial retreat rates in recent years on the Tibetan Plateau. This pattern is similar to that of the glacial shrinkages from the Maximum of the Little Ice Age to the present (Figure 5). The central part of the elliptical regional distribution with minimum rates of glacial retreat is located in the Tanggula Mountains, Kunlun Mountains, and Qiangtang Plateau of the inland of the Tibetan Plateau. In summary, it can be said that the glacial retreat rates increase from the inland to the margins of the Tibetan Plateau and reach their maximum on the Southeast Tibetan Plateau and Karakorum Mountains.

Causes for the negative Glacial mass balance and Glacial retreat in the chinese part of High Asia

The glacial mass balance is the sum of glacial mass income (precipitation on the glacier) and glacial mass loss (glacier melt) in the glacier system. A positive sum indicates a positive glacial mass balance and vice versa. The present glacial retreat pattern in the Chinese part of High Asia is closely related to the strong negative glacial mass balance in recent years. The continuous observation sites of glacial mass balance in the Chinese part of High Asia include the Glacier No.1 in the Urumqi River Basin (1956–2001), the Small Dongkemali Glacier in the Tanggula Mountains (1990–2001) and the Meikuang Glacier (1990–2001) in the Kunlun Mountains. Figure 6 shows the mass balance fluctuations of these glaciers in recent years.

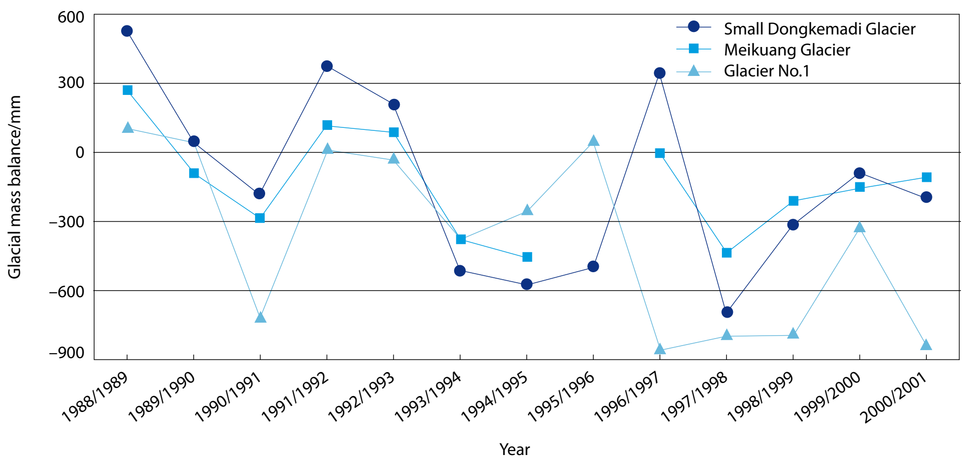

Figure 6
Glacial mass balances of some glaciers in the Chinese part of High Asia

Obviously, the mass balance of these glaciers cannot reflect the pattern of the whole Chinese part of High Asia. But the analysis of this data can at least help us to understand the retreat trends of the whole Chinese part of High Asia.

There are several distinct features in the glacial mass balance of these glaciers: The glaciers retreated most intensively in the Tianshan Mountains and the glacier mass balance of the glaciers of this region was strongly negative all the time. The advancing glaciers on the central and northern Tibetan Plateau recently shifted into a retreating state recently and their mass balances shifted from positive to negative. Figure 6 also illustrates that the mass balance of Glacier No.1 in the Tianshan Mountains remained strongly negative all the time. In fact, its absolute value was the lowest among the three glaciers. The glacial mass balance of the Meikuang Glacier was very similar to that of the Small Dongkemadi Glacier. They were mostly positive before the 1990s, which coincides with the advance of the two glaciers before the 1990s. The mass balances of both glaciers started to become negative in the mid-1990s. It was a strong signal of the general retreat of the glaciers in the Chinese part of High Asia.

As mentioned above, negative glacial mass balance is the direct cause of glacial retreat in the Chinese part of High Asia. Precipitation amounts in most parts of the study region are increasing indicating that the main glacial mass income factor is not responsible for the shift of the glacial mass balance to negative values. On the other hand, numerous studies show that air temperatures are clearly increasing in the Chinese part of High Asia. Therefore, the key cause of the widespread glacial retreat in the study region seems to be global warming.

The Significance of glacial retreat in the Chinese part of High Asia on water resources in Northwest China

In order to study the impact of the glacial retreat in the Chinese part of High Asia on the water resource of Northwest China, it is necessary to first determine how much glacial ice has melted since the glacial retreat started in the 1960s – 1970s. This problem cannot be solved using observation results due to the low number of monitoring sites. However, it is feasible to estimate the amount based on the observation data. One method to do that is to estimate the amount based on glacial area (S) and glacial volume (V). Liu Shiying et al. (2002) proposed the following experimental equation based on numerous glacial observations:

$$V=0.034S^{1.43}$$

The results calculated with this equation are approximate values as the relation of glacial area (S) and volume (V) will change with glacier size. Another method is to estimate the glacial volume based on studying the relationship between glacier length, area, and volume at locations where glacier observation data are available. Glacier No.1 in the Urumqi River Basin is a site that has very detailed glacial observations, which can be used to estimate glacial fluctuation of other glaciers with the described method. But Glacier No.1 is only one glacier and the result estimated with this method in the present study should also be considered an approximate. Accordingly, the two methods will be used independently, and results will be compared.

Concerning the relationship between glacial length, area, and volume of Glacier No.1 in the Urumqi River Basin, Yao Tandong and Shi Yafeng (1990) found that the glacier volume had decreased by 38 %, while glacier area decreased by 33 % and glacier length decreased by 21 % from the Little Ice Age to 1988. From their studies, the change of glacier volume was the highest and the decrease ratio of glacier volume (V), glacier area (S) and glacier length (L) was 1.87:1.57:1. Shi Yafeng et al. (2001, 2002) studied the glacial fluctuations for the recent decades and found that glacial volume had decreased by 16.8 %, glacial area decreased by 13.8 % and glacial length decreased by 12.4 % from 1964 to 1992. Again, the decrease of the glacial volume was the highest and the V:S:L ratio was 1.4:1.1:1. Chen Jianming et al. (1996) also found similar ratios for Glacier No.1. Liu Shiyin et al. (2002) studied the glacial fluctuations in the West Qilian Mountains. He found that since the Little Ice Age the glacial volume decrease (14.1 %) is higher than glacial length decrease (11.5 %). However, when he studied the glacial fluctuation from 1956 to 1990 in the same region, he found that the glacial area decrease was 10.3 %, which is a little more than glacial volume decrease (9.3 %). Nevertheless, many facts confirm that the decrease of glacial volume is larger than glacial area since the Little Ice Age. It is easier to obtain glacial length than glacial area and volume. Taking the observation data of Glacier No.1 as an example, we can use the two V:S:L ratios mentioned above as Methods 1 and 2 and the ratio of the Qilian Mountain by Liu Shiyin as Method 3 to calculate the glacial volume change based solely on the glacial length fluctuation data. The average decrease of glacial length in the Chinese part of High Asia is about 5.8 % over the past 40 years based on observational data. Table 2 shows the decrease of glacial volume in the study region calculated with the three methods based on an assumed glacial length decrease of 5.8 %. The data in table 2 indicates that the glacier volume in the Chinese part of High Asia had decreased by 8.1 % and the glacial area decreased by 6.3 % in the past 40 years based on the V:S:L ratio of 1.4:1.1:1 and a glacial length decrease of 5.8 %. The total glacial area in the study region is 59406.15 km^2 and the total glacial volume in China is 5589.76 km^3. The average glacial depth in the Chinese part of High Asia is about 94 m, and a glacial depth thinning of 8.1 % is equal to 452.770 km^3 in ice volume with the glacier area decrease of 6.3 % amounts to about 3790.11 km^2. The glacial depth in the Chinese part of High Asia was estimated to have thinned, on average, by about 6.8 m, which is equal to a 0.2 m per year thinning in the past 40 years. According to a recent study, the annual thinning of glaciers in Alaska is about 0.52 m (Su Zhen et al., 1996, 1999), which is slightly more than what was estimated for in our study region. The glacial volume decrease in the High Asian part of China was estimated between 324.206 km^3 (third method in Table 2) and 586.924 km^3 (second method in Table 2) over the past 40 years.

To use the experimental formula of Liu Shiyin to estimate the glacial volume decrease, the average glacial area and its decrease in the past 40 years has to be known. According to our study the glacial area in the Chinese part of High Asia decreased by about 7 % in the past 40 years. Consequently, the result calculated with the experimental formula indicates that glacial volume decreased by $500 \times 10^9 m^3$ in the past 40 years. The results estimated with the two different methods are comparable. We think that an estimated decrease of glacial volume between 452.77 km^3 and 586.92 km^3 for the Chinese part of High Asia over the past 40 years is reasonable. Although the result is an estimate, the figure clearly indicates the importance of glacial retreat to the water resources of Northwest China. If we assume a glacier volume loss of 502 km^3, the average of 452.77 and 586.92 km^3, the ice volume lost is equal to the sum of six years of total runoff in Xinjiang. The glacial volume decrease provides additional water for river runoff. A recent study of Shi Yafeng et al. (2001, 2002) showed that the runoff of many rivers in Xinjiang had increased considerably. The increase of total runoff of six tributaries of the Tarim River increased sharply and the increase of the annual runoff of the Aksu River is particularly intensive.

Because the Tarim River Basin has the highest concentration of glaciers in the High Asian part of China, it is very important to study the impacts of glacial fluctuation on the water resources in the Tarim River Basin. There are 14285 glaciers in the Tarim River Basin with a total area of 23628.98 km^2, a volume of 2669.435 km^3, and an average glacial depth of 113 m. Liu Chaohai et al. (1999) reported a similar data set of 12182 glaciers with an area of 20271.02 km^2 and a volume of 2347.317 km^3 for the Tarim River Basin. Table 3 shows the results for the glacial volume decrease in the Tarim River Basin calculated with the data from this paper. The magnitude of glacial change in the Tarim River Basin was much larger than that in the Tianshan Mountains and the glacial length decrease reached 13.8 %. The highest value of glacial volume decrease ($280 \times 10^8 m^3$) listed in table 3 (calculated with the second method of Table 2) seems to be the most reasonable. The glacial volume decrease calculated with the experimental formula is $222 \times 10^8 m^3$. Again, the estimation results using the two different methods are comparable. According to a previous study (Shi Yafeng et al., 2002), the total annual runoff of six tributaries of the Tarim River is $310 \times 10^8 m^3$.

Table 2 Glacial volume decrease in the past 40 years calculated with different methods

Methods	Glacial length decrease ratio (%)	Glacial area decrease ratio (%)	Glacial volume decrease ratio (%)	Glacial volume decrease ($\times 10^9 m^3$)	Glacial depth thinning (m)
1.4:1.1:1.0	5.8	6.3	8.1	452.770	6.8
1.81:1.57:1.0	5.8	9.1	10.5	586.924	10.9
1.0:1.0:1.0	5.8	5.8	5.8	324.206	5.8

Table 3 Glacial volume decrease in the Tarim River Basin calculated with different methods

Methods	Glacial length decrease ratio (%)	Glacial area decrease ratio (%)	Glacial volume decrease ratio (%)	Glacial volume decrease (volume) ($\times 10^9\,m^3$)	Glacial depth thinning (m)
1.4:1.1:1.0	5.8	6.3	8.1	216.224	9.8
1.81:1.57:1.0	5.8	9.1	10.5	280.291	12.7
1.0:1.0:1.0	5.8	5.8	5.8	154.827	7.0

Therefore, the contribution of melt water from the glacier volume decrease to the runoff of the Tarim River reached about 50 % in the past 40 years, which is equal to a net supply of 13 % per 10 years. According to a study by Shen Yongping (2003a), a stronger glacial melting period started in 1972/1973. If he was correct, the net supply of melt water from glacial volume decrease would have been much larger after 1972/1973. According to a study by Shi Yafeng et al. (2002), the runoff in the Tarim River Basin increased from $310 \times 10^8\,m^3$ to $350 \times 10^8\,m^3$ in the 1990s, which is equal to a runoff increase of 13 %. According to his study, the climatic warming and wetting are the major causes of runoff increase in the Tarim River Basin. The results show that the climatic warming and the associated glacial melt water increase are very important in this area. According to a study of the mass balance change of the Tailan Glacier in the upper reaches of the Tarim River Basin in 1997 by Sheng Yongping (2003b), glacial depth thinned by 1.6 m with an average thinning of 0.29 m per year between 1957 and 2000 and the supply of the melt water of the Tailan Glacier reached 13 % between 1957 and 1986 and 23 % between 1987 and 2000. That is to say, the proportion of glacial melt water in total runoff increased by 10 % in the 1990s, a value similar to the above estimation.

According to a study by Yang Zhenniang (1991) and Yang Zhenning and Hu Xiaogang (1992), the glacial melt water runoff in the Tarim River Basin was $202.26 \times 10^8\,m^3$. If the glacial melt water runoff began to increase in 1972/1973, a glacial ice volume decrease of $280.291 \times 10^8\,m^3$ would result in an increase of glacial melt water contribution to runoff by 5 % a year since 1972/1973.

However, the air temperature increase was generally not particularly pronounced in the 1970s. Evident climatic warming started in the 1980s, and the glacial melt water runoff supply should, therefore, have noticeably increased since the 1980s. A study of Ye Baisheng et al. (1999) showed that the runoff in Xinjiang has in fact increased by about 32 % since the 1980s.

According to studies by Wang Zongtai and Yang Huian (1991) and Yang Huian et al. (1996), there are 24752 glaciers in Gansu, Qinghai, and Xinjiang, with a total glacial area of 31351.09 km^2, a glacial volume of 3107.8 km^3, and an average glacier depth of 99.1 m. The glacial volume decrease caused by the glacial retreat in Northwest China can also be estimated with the methods of Tables 2 and 3, and the results are shown in table 4. The number estimated using the experimental formula is $258 \times 10^9\,m^3$. It is within the range of the values estimated using the relationships between glacial length, area, and volume.

According to studies of Yang Zhenniang and Hu Xiaogang (1992) and Yang Zhenniang (1995), the annual glacial melt water runoff in China was about

Table 4 Estimations of the glacial volume decrease in Northwest China

Methods	Used glacial length decrease ratio (%)	Used glacial area decrease ratio (%)	Used ice volume decrease ratio (%)	Ice reserves (volume) decrease ($\times 10^9\,m^3$)	Glacial depth thinning (m)
1.4:1.1:1.0	5.8	6.3	8.1	251.732	8.6
1.81:1.57:1.0	5.8	9.1	10.5	326.319	11.6
1.0:1.0:1.0	5.8	5.8	5.8	180.252	6.1

$56.4\,km^3$ or $564 \times 10^8 m^3$, which is close to the total annual runoff of the Yellow River, and amounts to 2 % of the total runoff in China, 10 % of the total runoff in Northwest China and 13 % of the total runoff ($4431 \times 10^8 m^3$) of West China's Gansu, Qinghai, Xinjiang, and Tibet. In fact, glacial water resources are very important for the arid inland in Northwest China's Xinjiang, Qinghai and Gansu. According to the results of Yang Zhenniang (1995), the total glacial melt water runoff in Northwest China was about $220.07 \times 10^8 m^3$. Using the upper limit of the estimated glacial volume decrease in table 4 ($326.319 \times 10^9 m^3$) and assuming that intensive glacier melt began in 1972/1973, the contribution of glacial melt water to runoff reached 5.5 % over the past 27 years. According to Yao Tandong et al. (1996, 1997), obvious climate warming occurred in the 1980s and became even more intensive in the 1990s. It could, therefore, be concluded that the supply of glacial melt water to total runoff was more than 5.5 % in the 1990s.

Conclusions

The glaciers in the Chinese part of High Asia are currently retreating intensively under the impacts of global warming. The glacial retreat progression can be divided into several stages during the 20th century. Glaciers generally advanced or shifted from an advancing to a stable state during the first half of the 20th century. From the 1950s to the late 1960s, the glaciers in the Chinese part of High Asia retreated on a large scale. Subsequently, the retreat slowed down in the 1970s and reintensified again in the 1980s. The glacial retreat in the 1990s was the most intensive. During this period, most advancing glaciers shifted to retreat. The glacial retreat was most intensive on the southeast Tibetan Plateau and in the Karakorum Mountains and weaker on the central Tibetan Plateau.

The glacial retreat in the study region and the negative glacial mass balance are a result of global warming. The long-term observation data of several glaciers showed that the positive glacial mass balances between the end of the 1960s and the late 1970s had caused the glacial firnline to drop. At that time, the number of advancing glaciers increased and that of retreating glaciers decreased. In the 1980s, the majority of the glacial mass balances became negative again. In the 1990s, they showed the most negative values. The few glaciers that still had a positive glacial mass balance up to then also shifted to negative balance. The glacial retreat in the 1990s was the most intensive compared with any other periods during the 20th century.

The general glacial retreat in the Chinese part of High Asia during the 1990s caused a great amount of glacial volume decrease, which resulted in an increase of the contribution of glacial melt water to the runoff of the rivers in Northwest China. The glacial retreat caused glacial melt water runoff to increase by more than 5.5 % in the 1990s in Northwest China. In the Tarim River Basin, which has the highest glacier concentration, the net water supply from glacial retreat reached 13 % of total runoff over the past 10 years. Although the calculations yield only approximate values, it clearly shows the important impact of glacial retreat on the water resources in Northwest China.

Acknowledgements
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Present and future impact of snow cover and glaciers on runoff from mountain regions – comparison between Alps and Tien Shan

Ludwig N. Braun and Wilfried Hagg

The aim of this contribution is to show how snow- and glaciermelt influence runoff today and in the future under the assumption that global warming continues. This assumption will not necessarily come into effect, but according to climatologists, the opposite is rather unlikely in the next few hundred years, for example a drastic cooling due to changes in ocean currents. Mountain regions receive more precipitation than the lowlands around them, and act as a reservoir of this excess water by temporarily storing it in the form of snow and ice.

Melt is highest during warm and dry periods and thus runoff increases during times of drought. This release from snow and ice storage ensures a reliable water flow in rivers, and thus is of great value in terms of irrigation and other water uses. Glaciers, therefore, influence the water cycle very favourably by collecting water during times of abundance and releasing it when there is a lack of precipitation.

Even in a warmer climate we expect precipitation to fall abundantly in the mountains, but more and more in the form of rain rather than snow, and therefore the character of runoff will change from a glacial or nival regime towards a pluvial one. This will produce a less reliable water yield and the absence of glaciers will lead to water shortages during hot and dry summers, when water is needed most urgently for irrigation and drinking water. Therefore, we need to develop strategies to adapt to the situation that rivers will run dry more often in the future.

Introduction – Hydrological importance of glaciers

Only about 1 % of worldwide ice is stored in mountain glaciers. However, this small fraction is of primary importance to mankind, especially in arid regions such as Central Asia, where the release of water from snow and ice storage favourably influences discharge in mountain streams. The hydrological significance of mountain ranges in maintaining a sustained water yield to the surrounding lowlands has been shown by Viviroli and Weingartner (2004). According to their study, the Amudarja River is highly dependent on mountain water supply, whereas the Alps are located in a more humid and temperate region, and therefore have a rather moderate hydrological significance. Mountain regions are “water towers”, because they yield an above-average discharge and they store water and redistribute it over time. Snow cover provides seasonal storage, and glaciers influence the hydrological regime on a time scale of years and decades. Meltwater causes discharge to increase in times of drought, and therefore reduces runoff variablity.

This so-called “compensating effect” of glaciers on runoff can be shown by the mass balance and runoff time series of Grosser Aletschgletscher, the largest glacier in the Alps (Figure 1). During the cool and wet years of World War I, excess water was stored in the glacier, resulting in a reduction of runoff in Massa River (basin area of 195 km²). In contrast, the period during World War II and after was characterized by hot and dry summers, the mass balance of Aletschgletscher was significantly negative, and runoff was clearly above average. At the Rhone River (basin area 5220 km²), the impact of this long-term storage and release is less pronounced on an annual timestep.

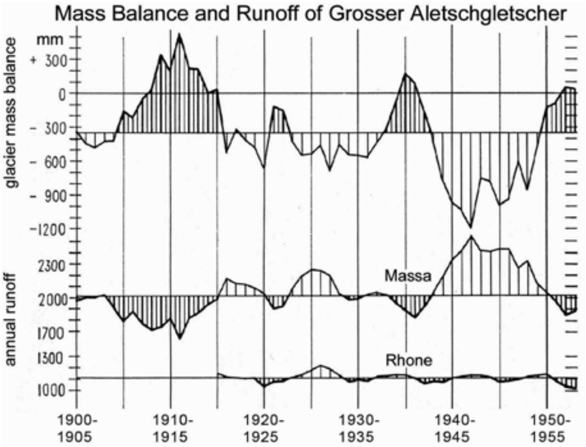

Figure 1 *Mass balance and runoff of Grosser Aletschgletscher, Switzerland (Kasser 1959, slightly changed). 5-years running mean.*

Glaciers and runoff in Central Asia

A very valuable source of information concerning the significance of snow and ice worldwide can be found in The World Atlas of Snow and Ice Resources (Kotlyakov *et al*. 1997), which shows a specific annual runoff of over 1000 mm for the Tien Shan mountains just south of Almaty, where Tuyuksu glacier is located (Figure 2).

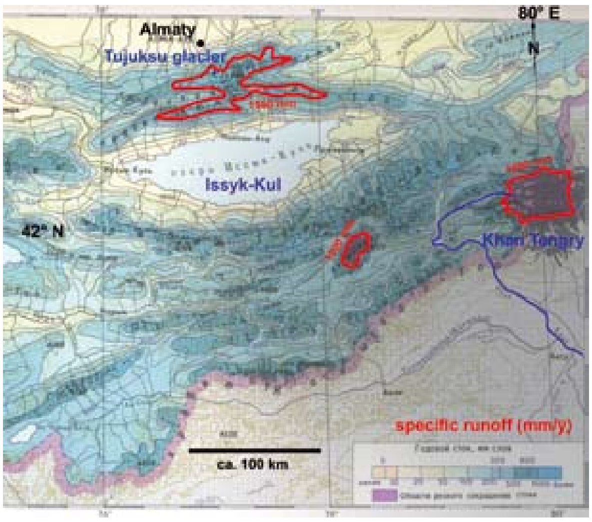

Figure 2 *Specific runoff in the Tien Shan mountains, source: Kotlyakov* et al. *(1997).*

The Pobeda-Khan Tengry massif is also a source region of high water yield, with much more than one meter of specific annual runoff. Figure 3 shows how this annual runoff is distributed through the year, based on the example of the Chon-Kyzylsu basin.

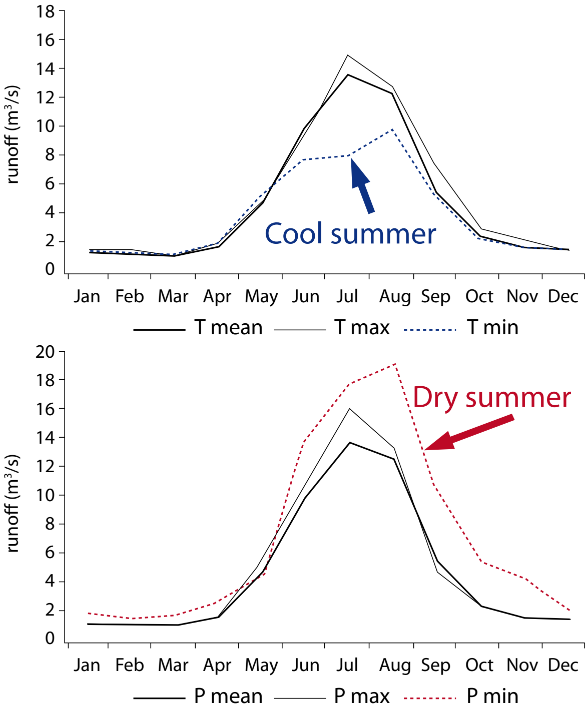

Figure 3 *Compensation effect of glacial discharge, Chon-Kyzylsu basin, glacierization 29 %, Terskey Ala-Too Range (Dikich & Hagg, 2004).*

Most of runoff occurs during the months of May to September, that is during the growing season. During cool summers melt rates are reduced, and therefore discharge is below average. In dry summers runoff is above average, because ice melt rates are higher than usual. The “compensating effect” of glaciers is very well demonstrated here: the lack of water due to the absence of rain is compensated by excess melt, and therefore a reliable water yield is delivered due to the presence of glaciers.

The high significance of snow- and glaciermelt has been long recognized in the literature, for instance by Shults (1965) who mentions an icemelt fraction of about 1/5th with respect to annual flow, but almost twice as much when looking at the summer months only. Aizen et al. (1996) have assessed the icemelt fraction in the Northern Tien Shan to be up to 70 % during the summer months and Dikich and Hagg (2004) confirm these figures.

Glazirin (1996) has shown that even a rather small portion of a glacierized area of 10 % of the total basin will yield a runoff fraction of up to 50 % from glaciers (Figure 4). This effect of augmentation of runoff due to glaciers is especially pronounced in so-called “concave” basins, which are steep at high elevation with glaciers reaching far down into the valleys. In basins of a "convex" nature, i.e., that are steep at low elevations with large glacier plateaus at high elevations, this effect is less pronounced. Glazirin (1996) could also show that even small glaciers can contribute favourably to total runoff.

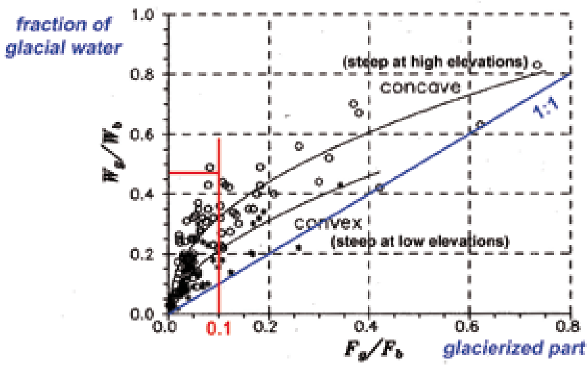

Figure 4 *The relationship between the part of glacial water (Wg) in the total annual river runoff (Wb) and the glaciation of river basin (Fg/Fb) when the hypsometric curves are convex (stars) and concave (circles). Taken from Glazirin (1996).*

Apart from glaciers, the snow cover storage term is important for the production of runoff in spring. A thorough assessment of the snow cover was presented by Schröder and Severskiy (2002). The map in figure 5 shows the mean water equivalent of snow at the end of the winter season in the Tien Shan mountains, with the city of Almaty showing an average snow accumulation value of approximately 100 mm.

No obvious trend can be observed in the duration of this snow cover in the past 70 years, (Figure 6) in contrast to low- and mid-elevation stations in the Alps, which show a clear trend towards shorter snow cover duration in the past 25 years.

Glaciers and runoff changes in the Alps

Vernagtferner is a glacier in the central eastern Alps and has been observed since the early 1960s. The long-term monitoring of Vernagtferner is the major task of the Commission for Glaciology of the Bavarian Academy of Sciences. Observations of the glacier mass balance over 40 years and the measurements of the individual terms of the water balance in the Vernagtferner basin show that average annual runoff has doubled from about 1200 mm in balanced years to about 2400 mm in recent years, with a peak of over 3000 mm in the record year 2003 (Figure 7).

At the same time, the glacier mass balance shows a clear trend to more negative values, showing a mean value of –500 mm in the last 10 years in comparison to 0 mm in the first 10 years of water balance recording. The glacier extent in this basin of about 11 km² in area was about 84 % at the beginning of measurements and is now down to 73 %.

There is no discernable trend in basin precipitation, and the obvious trend in discharge can be fully attributed to changes in glacier storage. When splitting the annual mass balance of Vernagtferner into the winter and summer balances, we can see that the accumulation conditions have been rather stable over

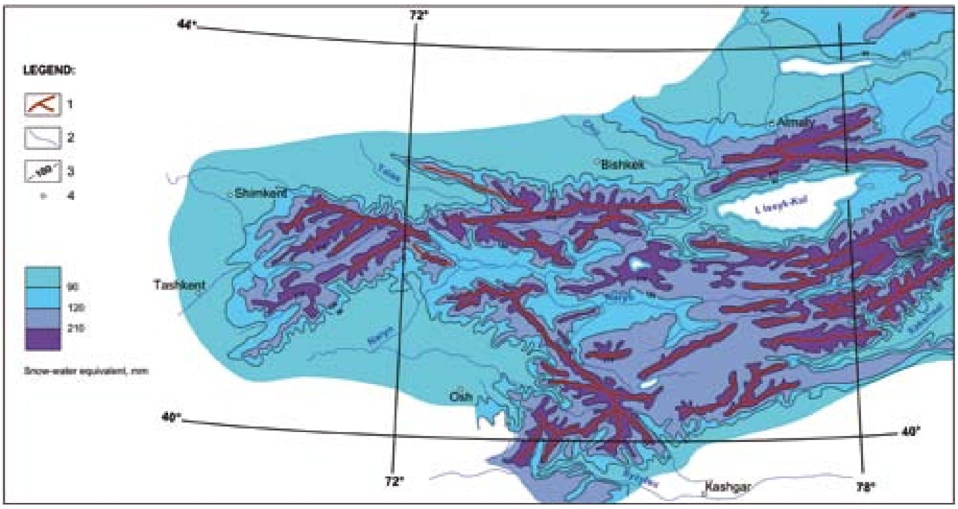

Figure 5
Snow-water equivalent in the Tien Shan, taken from Schröder and Severskiy (2002).

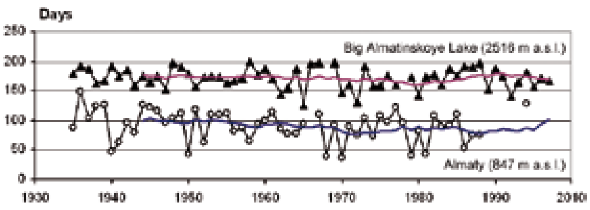

Figure 6 Duration of snow cover. Based on Pimankina, taken from Schröder and Severskiy (2002)

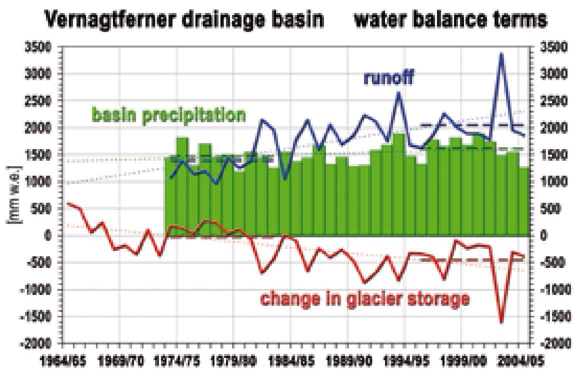

Figure 7 Water balance of Vernagtferner basin. Evaporation was derived externally and is in the order of 120 mm/y.

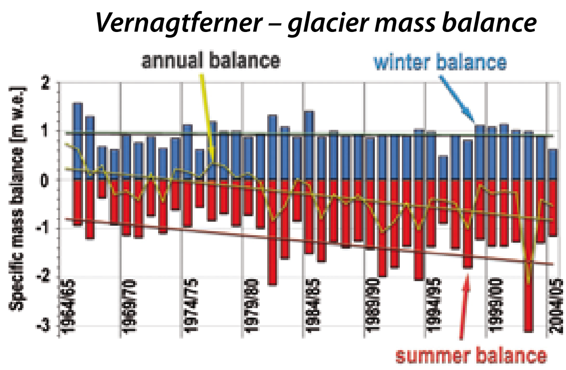

Figure 8 Glacier mass balance of Vernagtferner.

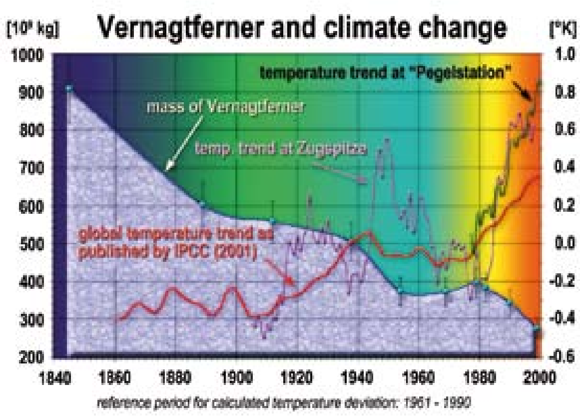

Figure 9 The mass loss of Vernagtferner against the background of global and local temperature curves.

the past 40 years, with a mean snow accumulation in winter of about 1000 mm, corresponding to a mean snow depth of about 2.5 m over the whole glacier (Figure 8).

However, the summer balances take on more and more negative values, from about –1000 mm in balanced years to values of about –1800 mm today, with a record value of –3000 mm in the summer 2003. A prolonged summer melting season is responsible for the excess melting.

When focusing on the more recent past and the Alpine region, we can see that during the last 120 years the temperature in the Alps has increased over 2 °C. This temperature trend can clearly be correlated to mass changes of Vernagtferner, which has lost about 3 quarters of its maximum mass in 1850 (Figure 9). The melting of this amount of ice needs a surplus of about 5 W/m² as a mean flux density. In comparison to the "natural" greenhouse forcing of about 250 W/m² as observed on a glacier, this value is only about 2 %.

Glacier changes in Central Asia

In Central Asia, a pronounced glacier retreat can be observed since the 1970s. Aizen et al. (2006) have made an assessment in the Akshiirak glacier area south-east of Issyk Kul (Table 1).

The past 60 years were split into 2 periods of 34 years and 26 years. The table above shows the changes in glacier area, changes in ice loss expressed as height changes, and loss in volume. Glacier changes are set in relation to changes of air temperature and precipitation. These figures show the acceleration in ice loss during the last decades.

Table 1 Glacier changes in the Central Akshiirak glacier massif (Aizen et al., 2006)

	1943 – 1977 (34 y)		1977 – 2003 (26 y)	
Change in Area (km²)	18.0	–4.2 %	35.2	–8.7 %
Change in Height (m)	8.3		15.1	
Change in Volume (km³)	3.6		6.1	
Summer (May-Sep) air temperature change (Tien Shan Station, 3614 m a.s.l.)	+ 0.12 °C		+ 0.88 °C	
Annual precipitation change	–15 mm		–33 mm	

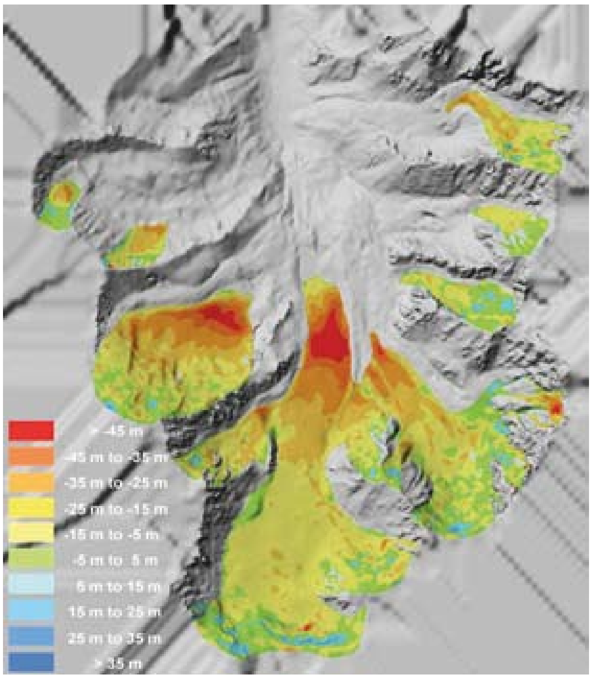

Figure 10 *Height differences of Tuyuksu glaciers 1958-1998.*

Another area with a long tradition of glaciological research is Tuyuksu glacier basin, 30 km south of Almaty. During the "Geophysical Year" in 1957/58 a German-Soviet research team produced a map at a scale of 1:10000 based on terrestrial photogrammetry. Exactly 40 years later, a new map was produced with the cooperation of the Institute of Geography of the Academy of Sciences of Kazakhstan under the leadership of Professor Igor Severskiy, the Commission for Glaciology, the Institute for Photogrammetry and Cartography of the Technical University of Munich, and the German Geodetic Research Institute (DFG) in Munich (KfG 2003). The new map can be compared directly with the earlier one. The change in glacier elevations over the 40 years can be derived, as shown in figure 10. The glaciers have lost 11 m as a mean over the whole area, and the glacier area was reduced by 20 % (Hagg et al. 2005).

Changes in glacier extent can also be shown for the Fedchenko glacier area situated in the Pamir mountains. The late founder of our Commission for Glaciology, Professor Richard Finsterwalder, visited the area in 1928, and an expedition of the Commission went there in 2002 to document the changes. A comparison of the photograph taken by Professor Finsterwalder in 1928 with the one from the German-Tajik expedition in 2002 shows a noticeable retreat in the tongue area of Muskulak glacier (Figure 11). The elevation change in the tongue area is about –30 m. When looking at other glaciers such as the Tanimas glaciers further to the west, only small reductions in size are observed. This fact may be due to the rather long response times of these large glaciers, and to the tendency towards higher precipitation values measured at the "Lednik Fedchenko Station" (elevation 4170 m) over the past 70 years as reported by Glazirin & Kodama (2003). As the major portion of precipitation falls as snow at these high elevations, snow accumulation may have increased in the past decades in this area of the Pamir mountains.

Runoff changes in Central Asia

With the continued mass loss, glaciers have developed a highly efficient drainage network that can transport glacier meltwater and runoff from heavy storms to the lower parts of the glacial basins very fast. A shrinkage of glaciers favours the occurrence and magnitude of glacial floods due to several factors. Firstly, the loss of firn (multi-year old snow) areas lowers the storage capacity for meltwater and leads to an increase of bare ice areas with low albedo (reflectivity) and high melt. Secondly, in years of large mass loss the glaciers develop a highly efficient drainage system.

All these processes can already be observed today, but how will runoff from mountain regions change under the assumption that global warming continues and glaciers will gradually disappear? This question was the

Figure 11
Tongue of Muskulak glacier 1920 and 2002, taken from the same location.

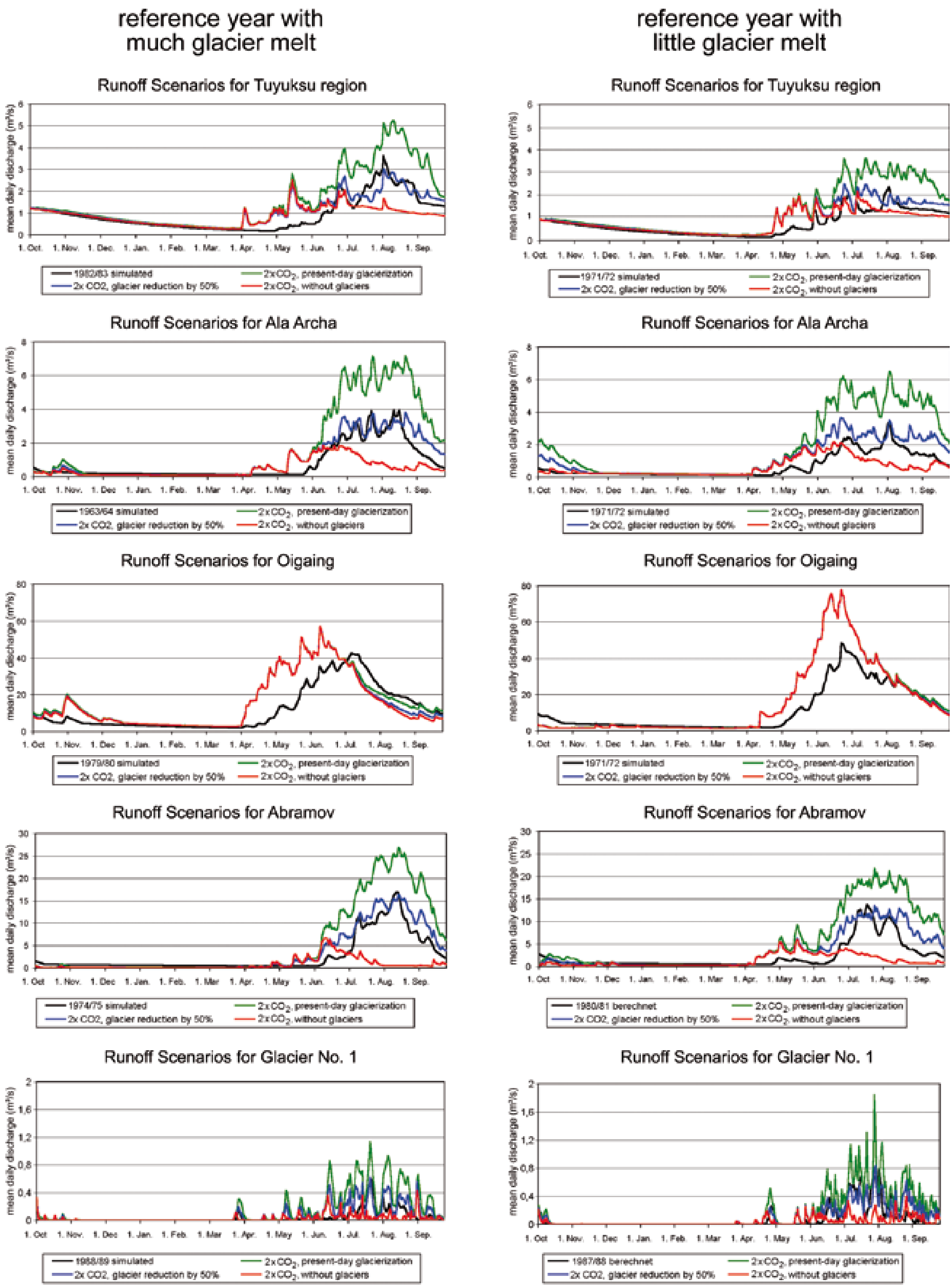

Figure 12 *Calculated daily discharge of the reference years and of a climate scenario after the doubling of* CO_2*, for three steps of deglacierization. Taken from Hagg* et al. *(2006).*

topic of two research projects in which the conceptual HBV-ETH runoff model was used to simulate daily runoff under current and future conditions in five glacierized catchments of Central Asia. The results from the test sites Tuyuksu (Kazakhstan), Abramov (Kyrgyzstan), Glacier No. 1 (China), Ala Archa (Kyrgyzstan) and Oigaing (Uzbekistan) are discussed in detail in several publications (Hagg 2003, Hagg and Braun 2005, Hagg et al. 2006, 2007). The model has a rather modest input data requirement, i.e. daily values of air temperature and precipitation.

A climate scenario (GISS model) for Little Almatinka valley is used, which assumes a doubling of CO_2 and predicts a warming of 4.2 °C and a precipitation increase of 17 % (Kazniimosk 1999). Model runs were carried out for present-day glaciation, for a reduction of 50 % and for the total disappearance of glacier areas (Figure 12). To cover the whole range of hydrological reactions, two reference years with differing meteorological conditions and glacier mass balances were chosen.

Figure 12 shows the hydrographs of the runoff scenarios. With present-day glaciation, runoff values are doubled. These conditions were actually observed in the Alps in the year 2003, however, it is unrealistic to assume that the present glacier extent will remain under the warmer climate as simulated here. A reduction of glacier area by 50 % could be realistic around the year 2050. This scenario still shows higher runoff values in spring that can be attributed to an earlier and more intense snowmelt, but runoff peaks in summer show the same amplitude as shown under present-day conditions, although they appear more often.

When reducing the glacier extent to zero, a situation that could come into effect around 2100, we still observe high spring runoff due to intense snowmelt, but runoff from glacier icemelt is drastically reduced, causing a sharp decline in summer runoff, now deriving from liquid precipitation only. The reduction of summer runoff is most pronounced for the Abramov glacier basin, as this basin has the highest degree of glaciation today (~50 %).

Summary and Conclusions

A pronounced glacier retreat has been observed worldwide since the middle of the 19th century. Water yield from glacierized basins has increased due to the reduction of ice storage. Under present-day conditions flood hazard is at a high level, and will stay high as storm events are likely to increase in intensity in the future. With continued global warming the glaciers will eventually disappear. Water yield will be reduced drastically in dry summers. In a warmer climate, precipitation amounts are likely to be greater, however, the individual events will be more intense. The runoff regime is shifted from “glacial-nival” to “pluvial”, and as the year-to-year variation of precipitation is high, runoff is less dependable because the compensating effect of glaciers is lost.

It can be concluded that monitoring of snow and glacier resources needs to be continued, because the “Global Change experiment” now underway needs to be documented. Measured changes in glacier mass and extent are the “hard facts” of climate change, and climate model scenarios need to be tested against this reality. Since part of the future global warming no longer can be prevented anymore, much greater efforts need to be focused on adaptation strategies.

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Climate change and its impacts on glaciers and water resource management in the Himalayan Region

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The greater Himalayan region sustains about 150 million people. Glacial melt provides important contributions to river flow. The region is highly vulnerable with respect to climate chance. The report describes the impact of climate change on glaciers and consequently on water resources of the region.

Introduction

Climate change is currently taking place at an unprecedented rate and will have potentially profound and widespread effects on the availability of and access to water resources. The mean global temperature rose by 0.74 °C over the past century. The rate of warming in the Himalayan region has been even greater than global average (Shrestha et al. 1999; Liu and Chen 2000).

Climate is an important determinant of water resources. Rising temperatures associated with changes in precipitation and evaporation are predicted to lead to changes in soil moisture, river flow, and groundwater. Melting glaciers are early indicators of climate change unlike the response of the forests which is slower and takes place over a long period of time. The Himalayan region provides an ideal environment for monitoring the response of regional hydrology to climate change because of steep climate gradients across elevation and latitude. Mountain glaciers are important environmental components of local, regional, and global hydrological cycles. As the climate warms, the water resource factors may also change, as evaporation may well increase and the quantities, timing, and reliability of supply may change.

The greater Himalayan region sustains approximately 150 million people. Additionally, changes in this vast region impact the lives of over 1.3 billion people living in the basins of rivers originating in the Himalayans, and on almost 3 billion people when downstream coastal zones are taken into account (Xu et al. 2007). The Himalayas are shared by Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan and are interwoven with nine major river basins – the Indus, Ganges, Brahmaputra (Yarlungtsanpo), Irrawaddy, Salween (Nu), Mekong (Lancang), Tarim, Yangtse (Jinsha), and Yellow River basins (Huanghe). Glacial melt provides important contributions to river flow, varying from the lowest rate of 1.3 % for the Yellow River to the highest rate of 40.2 % for the Tarim and 44.8 % for the Indus basin (Table 1). Mountain hydrology is extremely sensitive to climate change and many glaciers in the region have retreated considerably in the last two decades. The formation and growth of many glacial lakes, possibly due to the rapid retreat of glaciers, could lead to catastrophic outburst floods (Vuichard and Zimmermann 1986).

Landscapes in the Himalayas form a complex mosaic of rocks, glaciers, alpine meadows and wetlands at high altitude, human settlements, farmlands, home gardens, lakes and rangelands at middle altitudes, and paddy and wetlands at lower levels. As a result, the Himalayas offer a range of habitats for all life forms and a diversity of livelihoods. Glaciers, as a source of water, have immediate impacts on human societies in the mountains and surrounding lowlands as people rely on fresh water for domestic purposes, irrigation, hydropower, and industrial use, as well as environmental flow and other ecosystem functioning. Glaciers, together with high altitude wetlands and lakes, are

Table 1 Principal rivers of the Himalayan region – basic statistics

	River		River Basin			
	Mean discharge (m^3/s)	Glacial melt in river flow (%)	Area (km^2)	Population x 1000	Population density (km^2)	Water availability (m^3/person/year)
Indus	5,533	44.8	1,081,718	178,483	165	978
Ganges	18,691	9.1	1,016,124	407,466	401	1,447
Brahmaputra	19,824	12.3	651,335	118,543	182	5,274
Irrawaddy	13,565	Small	413,710	32,683	79	13,089
Salween	1,494	8.8	271,914	5,982	22	7,876
Mekong	11,048	6.6	805,604	57,198	71	6,091
Yangtze	34,000	18.5	1,722,193	368,549	214	2,909
Yellow	1,365	1.3	944,970	147,415	156	292
Tarim	146	40.2	1,152,448	8,067	7	571
Total				1,324,386		

Source: IUCN/ IWMI, Ramsar Convention and WRI 2003; Mi and Xie 2002; Chalise and Khanal 2001; Merz 2004
Note: Hydrological data may differ depending on the location of gauging stations. The contribution of glacial melt is based on limited data and should be taken as indicative only.

considered 'water towers', as well as indicators of climate change and have impacts on sea levels. (Meier 1984). It has been estimated that about 30 % of the water resources in the eastern Himalayas are derived from the melt of snow and ice; this proportion increases to about 50 % in the central and western Himalayas and becomes as high as 80 % in the Karakoram. As a result of global warming, significant quantities of water are being released from long-term storage as glacier ice. In the short term this may result in an increase in water supplies (higher water levels in high altitude lakes and increased stream flows), but in the long term, as glaciers disappear, water supplies from glacial melt will decline. Water is necessary for all life forms, but it also can be dangerous and destructive (Weingartner et al. 2003). Intense seasonal precipitation during the Himalayan monsoons can trigger hazard events at different elevations. While snow avalanches and glacial lake outburst floods (GLOFs) predominate at very high elevations (>3500 m), landslides, debris flows, and flash floods are common in the mid-elevation mountains (500 – 3500 m). Floods are the principal hazards in the lower valleys and plains.

Mountain ranges also have a great deal of influence on local and regional climates and are considered a critical element of the climate system (Beniston et al. 1997). The Himalayas play an important role in the global climate. At mid latitudes, the Himalayas are one of the trigger mechanisms of cyclogenesis through their perturbation of large-scale atmospheric flow patterns. Seasonal blocking episodes with associated anomalies in temperature and precipitation are also closely linked to the presence of mountains that act as orographic barriers to the flow of moisture- bearing winds and control precipitation in neighbouring regions. The Himalayas are of fundamental importance to the occurrence of the monsoon in northern India and the arid conditions in continental Central Asia. Therefore, any irregularity in hydrometeorological processes in the vast mountain region can, in return, also have impacts on climate change.
In 2001 in an effort to address issues of climate change and water resource management, UNESCO and ICIMOD, together with Himalayan regional member countries participating in the 'Flow Regimes from International Experimental and Network Data Programme' (HHK-FRIEND), organized a training workshop on Mass Balance Monitoring of Himalayan Glaciers for technology transfer and study of linkages between climate change and glacier retreat (Kaser et al. 2003). Regional member countries with ICIMOD support carried out research to establish a glacial inventory as a baseline for monitoring glaciers in selected sites in Bhutan, China, Nepal, and Pakistan.

Hydrometeorological conditions in the Himalayas

Mountains display a great variability in hydrometeorological conditions: the western Himalayas and north-facing slopes are generally arid while the eastern Himalayas and south-facing slopes are generally humid. The Himalayas act as a barrier to atmospheric circulation for both the summer monsoon and the winter westerlies. The summer monsoon dominates the climate but is longest in the Eastern Himalayas, lasting eight months (March-October) in Assam, four months (June-September) in the Central Himalayas, and two months (July-August) in the Western Himalayas (Chalise and Khanal 2001).

Precipitation in the Himalayas has an east-west and north-south variation on the macro-scale. The east-west variation is based on the dominance of different weather systems. Figures 1a, b, c, d, and e illustrate these variations. In the western Himalayas the westerlies bring peak precipitation during winter (Figure 1a). The eastern Himalayas are influenced by the southwest monsoon with a dominant summer maximum (Figure 1c and e). Maximum annual rainfall is measured in Cherapunjee (Figure 1d). Wyss (1993) determined the area of the India/Pakistan border as the transition zone from one to two peaks with Peshawar showing two peaks (Figure 1b). A substantial amount of winter precipitation occurs as snowfall in this region (Shamshad 1988), whereas the role of the summer monsoon is negligible.

The monsoon rainfall is mainly of an orographic nature, resulting in distinct variations of rainfall with elevation and distinct differences between the southern rim of the Himalayas and the rain shadow areas of the Tibetan Plateau behind the main mountain range (Mei'e 1985). Alford (1992) identified the lower and intermediate altitudes as the main source of precipitation, suggesting that there is an increasing trend with altitude up to about 3500 m after which precipitation again decreases.

On the meso-scale the impacts of climate are mainly due to local topographic characteristics (Chalise and Khanal 2001) with dry inner valleys and the luv-lee effect (i.e., more rain on the windward side than on the sheltered side of a mountain). Examples of this are Pokhara and Jomsom located in western Nepal: Pokhara receives about 3500 mm annually, whereas Jomsom, only 60 km north of Pokhara but located behind the Annapurna Massif, receives only 270 mm per annum (Domroes 1978). The valley bottoms of the deep inner valleys in the high mountains receive much less rainfall than the adjacent mountain slopes. This suggests that the currently published rainfall amounts, which are mainly based on measurements taken in the valley bottom, is not representative for the area and major underestimations may result from the use of these data.

Temperatures vary inversely with elevation at a rate of about 0.6 °C per 100 m; and wide ranges of temperatures are found over short distances.

Local temperatures also correspond to season, aspect, and slope (Zurick et al., 2006). Owing to the thin atmosphere above the Tibetan Plateau and ample and intense radiation, the surface temperature has a large diurnal variation but the annual temperature range is relatively small. Temperature ranges in the northern mountain regions of Pakistan and Afghanistan are wide.

The temperature regime varies from tropical – with average annual temperatures of more than 24 °C in the eastern part (Myanmar and Bangladesh) – to alpine in the areas of the Qinghai-Xizang plateau and high mountain peaks with annual average temperatures below 3 °C Wyss (1993). Most of the areas on the southern rim of the Himalayas are sub-tropical with annual average temperatures of 18 to 24 °C, followed by small bands of warm-temperate and cool-temperate climates.

Potential evapotranspiration (PET) in the region reaches a maximum in the border area between India and Pakistan and shows a general decreasing trend from West to East and from South to North with increasing altitude (Wyss 1993). PET on the lower slopes of the Himalayas is about 1250 mm per year.

Availability of water in the Himalayan region

The focus of this research is solely on fresh water. Estimates of water availability for different countries in the Himalayan region vary greatly: the figures from Seckler et al. (1998) are given in table 2. Kayastha (2001) estimated a seasonal difference of 6100 m^3/y per capita assuming 8800 m^3/y per capita in monsoon season and 2700 m^3/y per capita in dry season. Within Nepal the per capita availability drops to 1400 m^3/y per capita in the Kathmandu Valley.

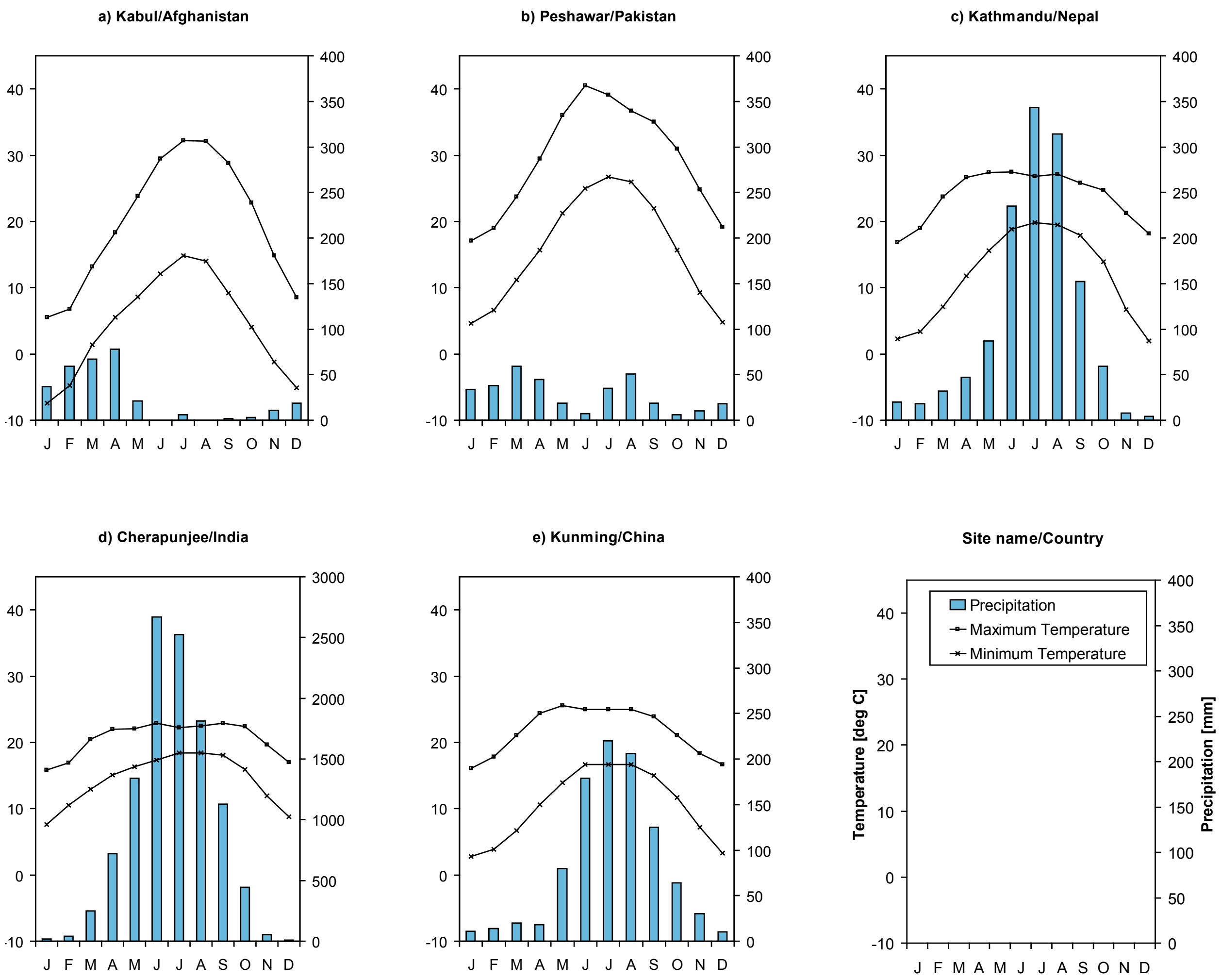

Figure 1 *Climatic diagram of five stations in a) the Hindu Kush, b) Western Himalayas, c) the Central Himalayas, d) the Eastern Himalayas, and e) Hengduan mountains (Data source: FAO, 2001; note: the precipitation axis in Cherapunjee is 8 times higher)*

Table 2 Water availability in Himalayan regional member countries (source for all countries: Seckler et al. 1998)

Country	Population (1990) Mio.	Annual water resources km^3/y	Per capita water availability m^3/y	Total withdrawals km^3/y	Per capita withdrawals m^3/y		
					Dom.	Ind.	Irr.
Afghanistan	15	65	4,333	256	102	34	1,566
Bangladesh	108	2,357	21,824	24	7	2	211
Bhutan	0.7		120,405				
China	1,155	2,800	2,424	533	28	32	401
India	851	2,085	2,450	518	18	24	569
Myanmar	42	1,082	25,762	4	7	3	91
Nepal	19	170	8,947	3	6	2	143
Pakistan	122	418	3,426	156	26	26	1,226

Key: Dom.: Domestic use, Ind.: Industrial use, Irr.: Irrigation use

Table 3 Criticality ratio for selected countries of the Himalayas (Seckler et al. 1998)

Country	Annual water resources km³/y	Total withdrawals km³/y	Criticality ratio CR %
Afghanistan	65	26	39
Bangladesh	2,357	24	1
China	2,800	533	19
India	2,085	518	25
Myanmar	1,082	4	1
Nepal	170	3	2
Pakistan	418	156	37

To define water scarcity Alcamo et al. (2000) used the criticality ratio (CR), i.e., the ratio of average annual water withdrawals to water availability. Summaries of water stress values are given in table 3 and show that Afghanistan and Pakistan are the most severely water-stressed countries in the region, followed by the two most populated countries in the world, India and China.

Climate change in the Himalayas

Observational records

The climate stations in the Himalayas are sparse and concentrated in proximity to settlements in valleys and might not adequately represent background conditions. Stations located in remote mountain areas often lack proper maintenance and inconsistencies in data collection due to poor accessibility render data of poor quality. The Himalayan region, including the Tibetan Plateau, however, has shown consistent trends in overall warming during the past 100 years (Yao et al. 2006). Various studies suggest that warming in the Himalayas has been much greater than the global average of 0.74 °C over the last 100 years (IPCC 2007; Du et al. 2004). Warming in the Himalayan region has also been progressively greater with elevation. For example, warming in Nepal was 0.6 °C per decade between 1977 and 2000 (Shrestha et al. 1999) (Table 4). There is also a tendency for the warming trend to increase with elevation on the Tibetan Plateau and in its surrounding areas (Liu and Chen 2000). Warming is furthermore greater particularly during autumn and winter.

Strong spatial and temporal variations exist in the rainfall distributions of Nepal (Shrestha et al. 2000). The seasonal mean rainfall is highest during summer monsoon and lowest during winter. Variability is highest during post-monsoon and lowest during monsoon seasons. Although the variability of the monsoon rainfall is small, the anomalies (too much or too little rain) on either side may have severe socioeconomic impacts. Precipitation data from Nepal do not reveal any significant trends.

In Pakistan mean temperatures exhibit mixed trends. Mean summer temperatures over all regions indicate an increase ranging from 0.03 to 2.17 °C. Mean maximum temperatures show higher increases than minimum temperatures. Summer monsoon rainfall has increased in all regions of Pakistan except for the Balochistan Plateau. Winter precipitation has decreased in the highland regions of Pakistan. The North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) have been found to have profound effects on winter precipitation in Pakistan (MoE 2003). Archer and Fowler (2004) found statistically significant increases in winter and summer precipitation and in annual precipitation in the Upper Indus basin. Temperature data from Skurdu and Gilgit indicate that

Table 4 Regional mean temperature trends in Nepal from 1977 – 2000 (°C per year)

Region	Seasonal				Annual
	Winter (Dec – Feb)	Pre-monsoon (Mar – May)	Monsoon (Jun – Sep)	Post-monsoon (Oct – Nov)	(Jan – Dec)
Trans-Himalayas	0.12	0.01	0.11	0.1	0.09
Himalayas	0.09	0.05	0.06	0.08	0.06
Middle Mountains	0.06	0.05	0.06	0.09	0.08
Siwaliks	0.02	0.01	0.02	0.08	0.04
Terai	0.01	0	0.01	0.07	0.04
All Nepal	0.06	0.03	0.051	0.08	0.06

Updated after Shrestha et al. 1999

there has been significant warming in these places in the past three decades. Mean daily maxima increased significantly more than mean daily minima. Winter temperatures increased more than annual temperatures.

In China, Liu and Chen (2000) analysed data from 97 stations distributed over the Tibetan Plateau. They found that significant warming ranging from 0.16 to 0.32 °C per decade had taken place. The greatest warming trend was observed in winter. The analyses of Liu et al. (2004) have clearly shown that warming is more significant in measurements from higher altitude stations than in those from lower stations. Gong (2006) studied the performance of 27 stations located within the upper Brahmaputra in Tibet and found temperature increases of 0.024 °C annually since 1959. In general, temperature increases accelerated during the two previous decades with greater changes in western Tibet than in eastern Tibet. Rainfall analyses from 27 stations in the Tibet Autonomous Region (TAR) of China in past decades (Gong 2006) show that there were increases in precipitation at 20 stations located in eastern and central Tibet and decreases in western Tibet.

The climate records for India are comparatively longer than others in the region and numerous studies on climate trends and variability have been carried out. Circulation of the Indian summer monsoon dominates rainfall over South Asia. All-India summer monsoon rainfall (AISMR) displays predominant inter-annual variability, marked by recurrent large-scale droughts and floods. Years of large-scale deficient and excess monsoon rainfall are usually identified with the criteria of the AISMR being below and above 10 % of the long-term mean, respectively. A remarkable feature of anomalous monsoon situations is the spatial coherence of seasonal rainfall anomalies over large parts of the country. The effect of drought are accentuated by the high coefficient of variability over regions of lower seasonal rainfall (Parthasarathy 1984) and their occurrence in two or three consecutive years on several occasions (Chowdhury et al. 1989).

An interesting new approach to monitoring surface ground temperatures is the borehole temperature profile, which represents high elevation mountainous sites and suggests a warming of ~0.9 °C over the past 150 years indicating that the warming began before the widespread changes in surface air temperatures. It is suggested that total warming for the 1980 baseline is 1.2 °C (Roy et al. 2002).

Possible future climates in the Himalayas

Based on regional climate models (RCMs), it is predicted that the temperatures in the Indian sub-continent will rise between 3.5 and 5.5 °C by 2100 (Rupa Kumar et al. 2006), those of the Tibetan Plateau are expected to increase 2.5 °C by 2050 and 5 °C by 2100 (Shi 2000). In one analysis carried out by the Pakistan Meteorological Department, the temperature is projected to increase by 0.1 °C per decade. Climate projections indicate increases in both maximum as well as minimum temperatures by 2 – 4 °C during the 2050s in India (MoEF 2004). Because of the extreme topography and complex reactions to the greenhouse effect, however, even high resolution climate models cannot give reliable projections of climate change in the Himalayas.

Consequences of climate impacts

Impacts can be expressed as functions of climate change and `vulnerability'. Vulnerability is measured by a series of biophysical and socioeconomic indicators. Biophysical indictors include glaciers, flash floods, forest fires, pests and diseases, water resources, tree-rings, and agricultural production. Socioeconomic indicators include per capita income, infant and child mortality rates, nutritional status, vector-borne diseases, fatal cardiovascular and respiratory disorders, drinking water, economic structure, and social services. Impacts can be negative or positive depending on the time, place, and sector that is looked at. Overall, negative impacts tend to dominate in the fragile mountain ecosystem and in the poorer regions of the Himalayas.

Glacial retreat and Glacial lake outburst floods

Glacial retreat

Glaciers react to the climate and, with the general warming trends, glaciers in the Himalaya, almost without exception, have diminished in volume over the plast few decades. Many Himalayan glaciers are retreating faster than the world average (Dyurgerov and Meier 2005) (Figure 2) and are thinning at the rate of 0.3 – 1 m/year. For example, the rate of retreat for the Gangotri Glacier over the last three decades has been more than three times the rate during the preceding 200 years (Srivastava 2003). Most glaciers studied in Nepal are undergoing rapid deglaciation: the reported rate of glacial retreat ranges from several metres to 20 m/year (Fujita et al. 2001; Fujita et al. 1997; Kadota et al. 1997). In the last half century, 82.2 % of the glaciers in western China have retreated (Liu et al. 2006). On the Tibetan Plateau, the glacial area has decreased by 4.5 % over the last twenty years and by 7 % over the last forty years (CNCCC 2007).

Such catastrophic reductions in ice cover have not been observed in the northwestern Himalayas, Karakoram, Hindu-Kush, or Pamirs. From the 1920s to the 1960s, the glaciers in these ranges exhibited the prevailing pattern of glacial retreat and ice mass reduction following the Little Ice Age. In the 1970s, however, many of these glaciers exhibited short-term thickening and expansion (Hewitt et al. 1989). Throughout the 1980s and most of the 1990s retreat and thinning again became the rule, but they were of a fairly gradual nature. In the Karakoram, there is widespread evidence of expansion, or downslope redistribution of ice, from the late 1990s onwards in more than thirty glaciers (Hewitt 2005). In addition, a large increase has been noted in the incidence of glacial surges compared to long-term records (Hewitt 2007). Moreover, since the 1960s, mean temperatures at valley weather stations have either remained unchanged or have declined, mainly as a result of cooler than average summers offsetting warmer than average winters (Archer and Fowler 2004). At the same time, since the 1950s various mountain communities

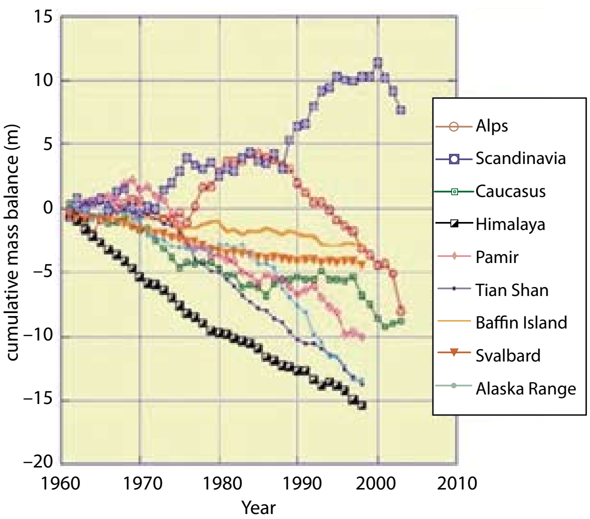

***Figure 2** Rapid retreat of Himalayan glaciers in comparison to the global average (Dyurgerov and Meier 2005)*

have been severely threatened by the diminishing of or disappearance of the small ice masses and snow fields on which they depend for water supplies. These are typically in watersheds situated at lower altitudes – not above 6,000 m – but there have been no studies to determine the scope and extent of changes in the many small ice masses in these ranges, or to determine changes in ice cover by elevation. These developments are certainly related to global climate changes, and they reinforce the need to recognise the diversity of responses in the greater Himalayan region.

Glacial lake outburst floods (GLOFs)

The formation and growth of glacier lakes is a phenomenon closely related to the deglaciation. As glaciers retreat they leave behind voids that fill with melt water to form glacial lakes. The loose moraine dams retaining glacial lakes are structurally weak and unstable and possess the danger of catastrophic failure, causing GLOFs. Principally, a moraine dam may break due to some external trigger or self-destruction. A huge displacement wave generated by rockslides or snow/ ice avalanches from the glacier's terminus into the lake may cause the water to overtop the moraines, create a large breach, and eventually cause the dam failure (Ives 1986). Earthquakes may also be one of the factors triggering dam break depending upon its magnitude, location, and characteristics. Self-destruction is caused by the failure of the dam slope and subsequent sudden drainage.

Inventories of glacier dammed lakes and occurrences of GLOFs have been undertaken (ICIMOD 2001a,b, 2003, 2004a,b,c, 2005b,c,d,e; Iturrizaga 1997; Che et al. 2004; Chan et al. 2005). The results for Pakistan indicate 728 lakes of which 45 are potentially dangerous: comparable figures for other regions are: Tibet, 441 lakes, 77 dangerous; Nepal 2315 lakes, 20 dangerous; Bhutan 2674 lakes, 26 dangerous; and India 356 lakes, 22 dangerous.

While the glaciers are in general in a condition of retreat, glaciers in Pakistan, especially in the Karakoram often experience surges thereby intercepting the flowing river and resulting in the formation of a glacial lake. There have been numerous outbreaks of such glacial lakes. Iturrizaga (1997 and 2005a) reports 20 such glacier-dammed lake outbreaks in Shimshal Valley, in the Karakoram Mountains. Similarly, there have been 19 glacial lake outburst floods in Karambar Valley in the Hindu Kush.

Impacts on water resources

Climate change is not just about averages, it is also a matter of extremes and is likely to affect minimum and maximum temperatures and trigger more extreme rainfall events. For the sub-continent, less rainfall in winter and increased precipitation in the summer monsoon are predicted. In high altitude areas, an increased annual average temperature will cause the thawing of perennial snow and ice. In the short term, this may lead to an increase in annual discharge in rivers since a great proportion of river water comes from snow and ice.

However, in the long run the annual discharge may decrease and the discharge in dry season decline, further limiting water supplies for communities downstream.

Besides causing catastrophic events including GLOFs and landslides, glacial shrinkage will have serious impacts on the hydrological regime of the region. For some rivers, e.g., the Indus and Brahamaputra in the upper reaches, glacial melt is important throughout the year, whereas for other rivers, such as the Ganges, it is important during the non-monsoon (lean) seasons. Climate change and its impacts on deglaciation will likely have serious implications for hydrology including agriculture and hydropower generation in Pakistan (MoE 2003), Nepal (Agrawala et al. 2003), and India (Johannesson 1997).

All of the three mainly snowfed rivers, the Karnali, Sapta Koshi, and Narayani, in Nepal show a declining trend in discharge. It has been estimated that 70 % of the flow in the Ganges during the lean period is contributed by Nepalese rivers mainly from snow and glacial melt sources. Disruption of the hydrological regime of Nepalese rivers is bound to have impacts on the flow of the Ganges as well. A separate study suggests that the number of flood days and consecutive days of flood events will increase (Shrestha et al. 2003).

The power sector of India, which is already facing a 10 % shortage, is suggested to be the hardest hit by climate change. A reduction in water from the mountains would affect the economy of the region by limiting hydropower production and hampering industrial productivity (Johannesson 1997).

A modelling-based study on the impact of deglaciation on river flow in India and Nepal suggests that that there will be an increase in river discharge in the near future causing widespread flooding in the adjacent areas. But, after a few decades, this situation will reverse and water levels in these rivers will start declining to a permanently decreased level. For the headwaters of the Ganges, flow volumes are projected to peak at between +20 and +33 % of the baseline within the first two decades and then recede to around –50 % of the baseline. In the headwaters of the Brahmaputra, there is a general decrease in decadal mean flows for all temperature scenarios: glaciers are few in this area and flows recede as the permanent snow cover reduces with increasing temperatures.

In certain parts of the Tibetan Plateau, glaciers play a key role in supplying communities with water for irrigation, drinking, and hydroelectricity. The runoff from glaciers is also essential for maintaining river and riparian habitats. There is growing concern about the impact that changes in glaciers may have on water resources in the headwater regions.

The effects of shrinking glaciers on water resources before 2050 were examined for several regions using the statistical data from China's glacier inventory. The volume of meltwater will peak at the beginning of this century. In some river basins, such as the Shule River in the Qilian Mountains, glacial meltwater can account for one-third or more of total river runoff. It is predicted that the meltwater volume of several medium-sized glaciers of 5 – 30 km^2 will increase, peaking around the mid century. For example, glacial meltwater currently represents 50 to 80 % of the total discharge from the Yarkant and Yurunkax rivers. It is predicted that glacial meltwater volume will increase by 25 to 50 % by 2050, and the annual discharge of seven major rivers of the Tarim Basin will increase. Inland watersheds in the Qaidam Basin and on the Qinghai-Tibetan Plateau are dominated by extreme continental-type glaciers that have low temperatures and retreat slowly. Temperature rises and increases in meltwater during the first half of this century are favourable to the development of animal husbandry and economic growth. In the maritime-type glacial regions of the southeast Tibetan Plateau and the Hengduan Mountains, however, precipitation is heavy and ice temperatures are high. A temperature rise here will exacerbate the glacial retreat perhaps causing frequent flooding and disasters from debris flow. Xie et al. (2001) studied glaciers in the basins of the rivers Ganges, Yarlung Zangbo, and the Indus, which together occupy one-third of the total glacial area in China and cover an area of 19,500 km^2.

Functional models of the variable glacial systems were established and applied to study the response of glacial runoff to climatic changes. The model simultaneously considered the effect of decreasing air temperatures, caused by rising equilibrium line altitude (ELA) and reduction in glacial area. The modelling results indicate that the glacial runoff fed by the marine-type glaciers with high levels of mass balance are sensitive to climate change, and take 10–30 years to reach a climax. The glaciers are then forecast to go back to an initial state in less than 100 years. The projected rate of increase in discharge of glacial runoff is small. During peak periods, the increase in discharge rate ranged between 1.02 and 1.15. In contrast, the glacial streams of continental-type glaciers, which have more rapidly decreasing rates of glacial area and storage, longer lifespans, and lower levels of mass balance, respond slowly to climate variations. They take over 100 years to climax, and hundreds of years to return to their initial state. At similar levels of mass balance, small glaciers respond more quickly to climate change and retreat more quickly than large glaciers. Glacial systems with very large elevation differences have the longest lifespan.

Conclusion

There is now adequate evidence that the climate in the Himalaya region is changing in a significant manner. This region is perhaps one of the most vulnerable regions in the world with respect to climate change. Ongoing climate change is most obvious in the widespread deglaciation in the region. Continued deglaciation is certainly a threat to the livelihoods of several hundred million people in the region who rely on glacial meltwater. Further threats could come from sudden glacial lake outburst floods or from slow changes in the hydrological regime of river basins. There are uncertainties related to the extent and timeframe of climate change and its impact on water resources. Clearly the predicted changes in hydrological regimes will not only have profound impacts on human lives and livelihoods through human health, agricultural production, industry and energy, but will also affect ecosystems in both the mountains and on the plains below. Societies will have to face the challenges of adapting to these changing situations.

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Review of hydrometeorological observations in Tajikistan for the period of 1990 – 2005

A. Finaev

The present study describes the hydrometeorological processes monitoring system in Tajikistan and its changes from 1990 to 2005. Until the early 1990s the processing of data supplied by the hydrometeorological stations was done at the Central Asian Regional Scientific and Research Hydrometeorological Institute (SARNIGMI), but with the end of the Soviet Union this service was terminated. As a result, gaps in the course of monitoring were not interpolated, and the processing of data proved to be very difficult. This study tries to explain what measures were taken to gain as much scientific value as possible from the data series.

Introduction

Since the early 1990s meteorological stations throughout the country carried out atmospheric observations. These observations were conducted at elevations from 300 m a.s.l. to 4169 m a.s.l. High-mountain stations are notorious for their complicated supply and expensive material provision due to their location and difficult access during winter. Therefore, food and other materials required to ensure continuous observations over the winter have to be supplied in summer by road and air transport. After the collapse of the Soviet Union and the decline of the economic situation, the Hydrometeorological Service of Tajikistan was unable to meet the needs of a number of high-mountain stations and to ensure their smooth activity. Many specialists left Tajikistan. A civil war that broke out has also negatively affected the situation. Thus, many stations stopped functioning by the mid-90s. The highest Gorbunov station located at the Fedchenko glacier had been operating since 1928 but ceased its activity in December of 1995, because its staff had to leave. In 1996, the amount of active stations dropped to 29 compared to 57 in 1991.

Upon the end of military actions and some improvement in the economic situation, combined with assistance provided by several international organizations, observations were being resumed in some locations. By the end of 2005 observations were carried out at 45 stations (Figure 1). Seven automatic meteorological stations and several hydrological posts monitoring river streamflow have been established since 2003.

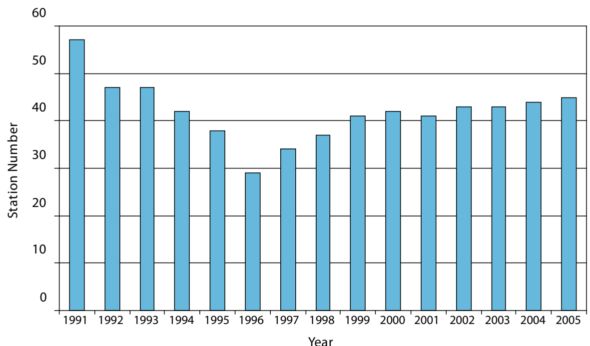

Figure 1 *Number of active hydrometeorological stations in Tajikistan from 1991 to 2005.*

The numbers of hydrological posts has also diminished. Of the 124 posts that operated in 1990, only 97 are still currently functioning. There were even fewer posts in the mid-90s.

From these statistics it becomes obvious that observations at many stations and posts are discontinuous for the last 15 years.

Another problem concerns the data processing. Before the early 90s of the past century, data supplied by stations and posts on paper were forwarded to the Central Asian Regional Scientific and Research Hydrometeorological Institute (SARNIGMI), where it was revised, processed, recorded on magnetic (digital) medium, issued as monthly bulletins, and sent back to Tajikistan. There is no such procedure at the moment. Information received from observation stations is kept in the archives of the National Hydrometeorological Service of Tajikistan (NGMS). However, the NGMS has no financial or human resources to process this data. Its employees only run the regular operations and meet the requests of other organizations. Therefore, we currently cannot expect to obtain comprehensive information from this region.

To analyze the hydrometeorological situation, we have selected a number of stations with available primary information. The records of stations located in valleys generally are more complete, while the records from mountain stations are more discontinuous. Furthermore, it should be noted that a user of this information cannot expect the data to be checked or corrected as evidenced by some obvious errors found in this study. However based on the information available, we are able to analyze the climatic and hydrological changes in the region over the last 15 years. Climate Reference Books were regarded as the norm (Climates of the USSR 1966, Vol. II. and Vol. IV).

Climate

Climate changes can be studied based on two parameters: temperature and precipitation. These parameters are not only major indicators of a change in climate but, generally, also represent the most continuous observational data sets.

Temperature

The observation results obtained from the climatological stations that were chosen for this study reflect the air temperature comprehensively as they were located in different regions and at different elevations. In the following Figures these stations have been sorted according to their elevation above sea level (ascending).

Long-term annual air temperature analysis shows a slightly positive trend within the study period (1990 – 2005) (Figure 2). All the stations show an almost synchronous fluctuations with small amplitude proving that there are temperature changes within the entire range of elevations covered by the selected stations. The maximum values were observed in 2001, with temperatures subsequently gradually decreasing up to 2005.

The temperature trends decrease with elevation above sea level (Figure 3). The highest temperature increase can be observed in the Southern valleys of Tajikistan, as indicated by the data from the Kurgan-Tube station

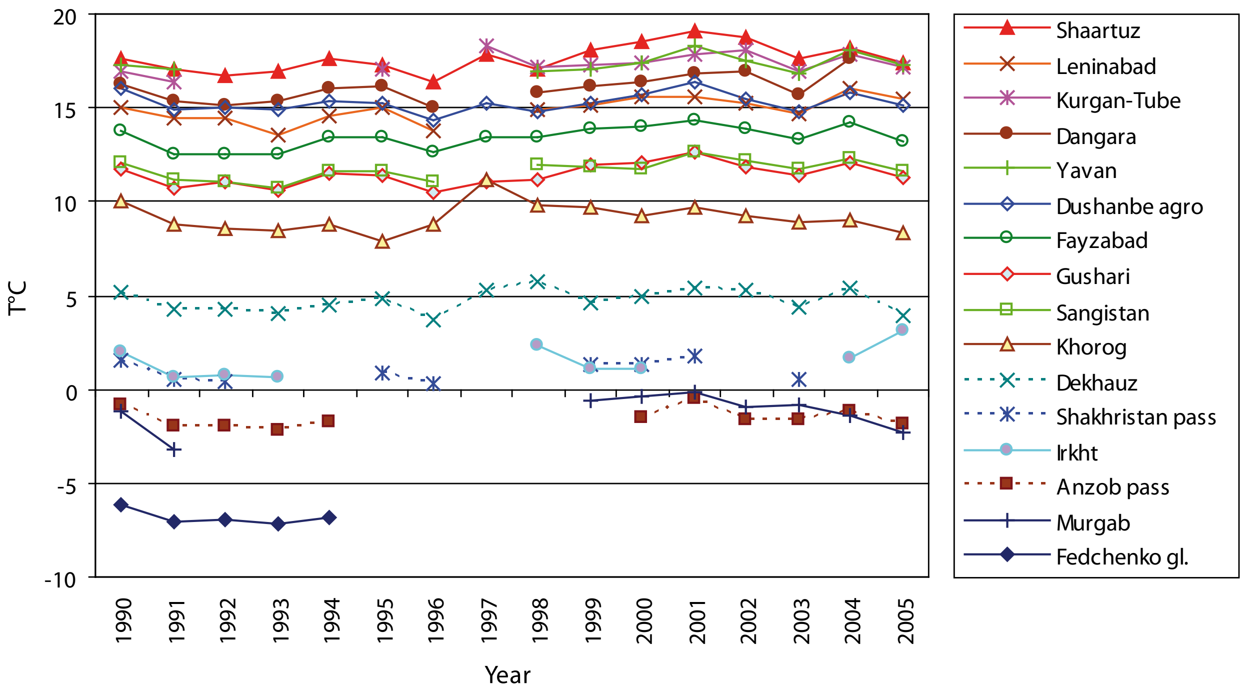

Figure 2 *Annual average air temperature [°C] at meteorological stations of Tajikistan.*

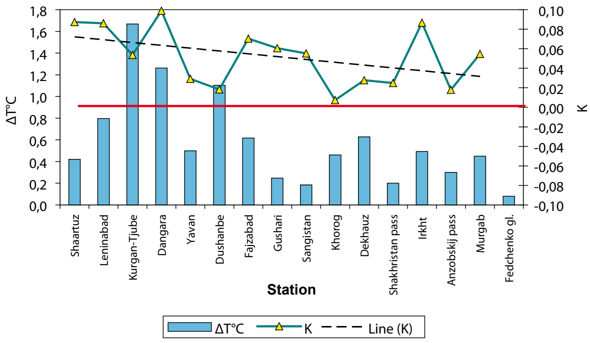

Figure 3 *Air temperature trend (ΔT), trend coefficient (K) and its linear function for the time period 1990 – 2005. Stations are placed according to their elevation ascending above sea level.*

(+ 1.7 °C). At high-mountain stations, the temperature increase is 0.7 °C – 0.2 °C. However, it has to be mentioned that the trend in Kurgan-Tube is likely overstated, since there is a gap in observations from 1992 to 1996. There are gaps in the data series of many other stations as well. Therefore, the obtained general temperature trend should be regarded as a reference point only and specific values of individual stations should not be taken too seriously.

If the long-term annual air temperature is approximated with a linear function, then a trend coefficient (K) can be calculated and used to show the temperature change rate. Figure 3 illustrates that the temperature change rate is decreasing with increasing elevations and that the Fedchenko Glacier actually has a negative value (K= –0,015, this station is not shown in the figure). However, the analysis for this location is somewhat unreliable as it has data during five years only (1990 – 1995). However, this five-year cycle can be analyzed based on data obtained from other stations. This analysis indicates that the period during which the Fedchenko Glacier station operated can generally be characterized as a descending branch of the temperature cycle.

Only six out of 16 stations have a complete data series. Furthermore, even the available data should be considered critically. For example, the abrupt increase of the average annual temperature in 1997 at the Khorog station is quite doubtful (Figure 2). Overall, an average temperature increase rate of 0,039 °C per year was calculated using all stations during the researched period.

An analysis of the seasonal temperature changes shows that the temperature trends are dissimilar for different seasons (Figure 4). The highest temperature increase is obtained for the winter period, especially in valleys. Values of up to 2.5 °C in Dangara and 2.4 °C in Kurgan-Tube, slightly more than 1 °C at the Gissar range and Pamir stations, and up to 0.5 °C in the East Pamir can be observed.

Precipitation

Precipitation is not evenly distributed over the researched area, since its intensity is strongly affected by the topography. Maximum precipitation amounts are observed at the Gissar range and in the Western foothills of Pamir. An analysis of the annual precipitation amounts shows that periodical fluctuations with an interval of about 5 years can be observed from 1990 to 2005 (Figure 5). These cycles are more evident and obvious, than those exhibited by the temperature data. Maximum amounts were recorded in 1991 – 1993, 1998, and 2003 – 2004. The highest fluctuations are observed at stations that also record the highest

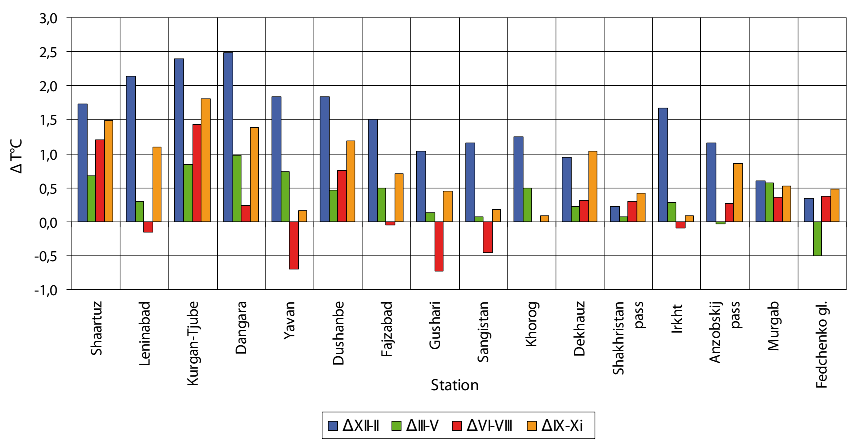

Figure 4
Seasonal air temperature trends. Winter (Dec-Feb); spring (March-May); summer (June-Aug); autumn (Sept-Nov).

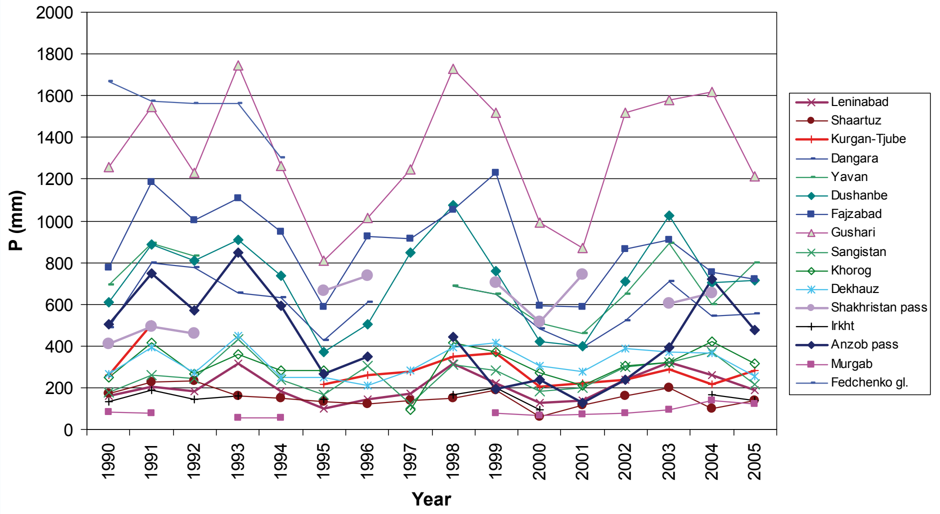

Figure 5
Annual precipitation in mm.

absolute amount of precipitation (Gissar-Alay). The intra-annual changes are much weaker in Pamir, especially East Pamir, and in the southern valleys.

Similar to temperature, continuous precipitation data series are available at six stations only. An analysis of annual precipitation shows that the recorded precipitation amounts were above the normal at almost all stations. Below normal precipitation amounts were only observed at the Shaartuz and Anzob pass stations. Further analysis reveals that stations at higher elevations experienced especially pronounced above normal precipitation amounts. Overall, the annual precipitation using all stations was 18 % above the normal during the study period.
The lowest temperature increases are observed for spring and summer. Some stations (Khudjant, Gushari, Sangiston, Yavan) even show a decrease of up to 0.5 °C for the average seasonal temperature in summer.

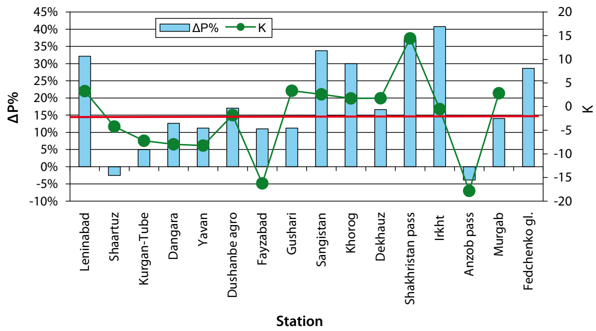

Figure 6 *Annual precipitation deviation from the long term normal (%) and trend coefficient (K), for the time period 1990 – 2005.*

Precipitation trends over the past 15 years were calculated for each station. The obtained trend coefficients are negative for valley stations and positive for mountain stations, with an overall average of +2.27 (Figure 6).

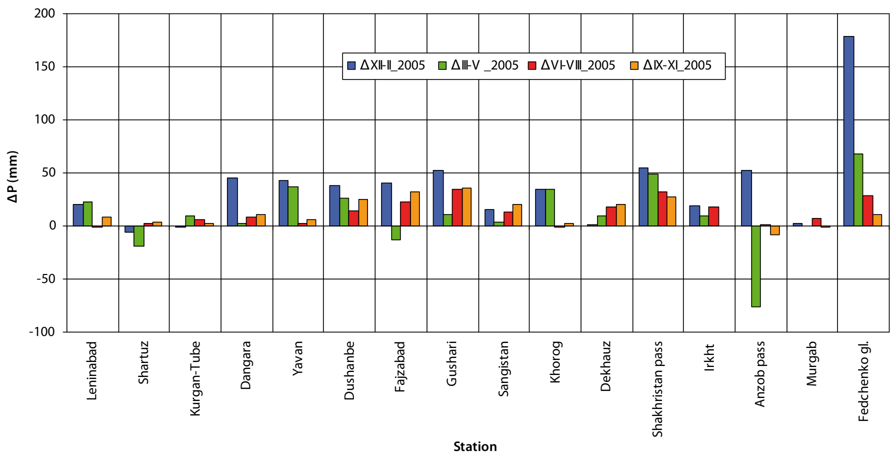

Figure 7
Seasonal precipitation deviation in mm.

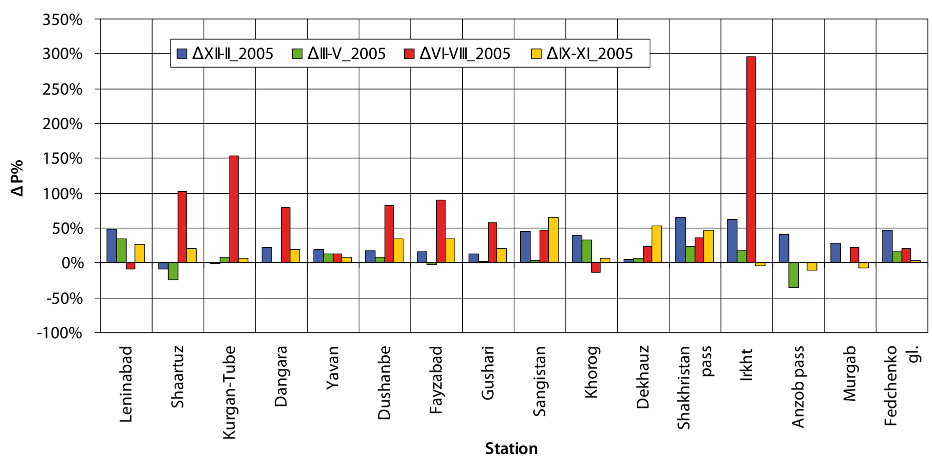

Figure 8
Seasonal precipitation trends in %.

Overall, no obvious trend could be identified. Precipitation decreased in the flat valleys of Southern Tajikistan but increased in the mountain regions of Gissar and Pamir-Alay. It is not possible to estimate a precipitation trend at Fedchenko Glacier because, as mentioned before, data is available for the first five years only.

The analysis of seasonal changes in precipitation amounts shows an increase of up to 50 % in valleys and high mountains and by 6 – 9 % in the mid-elevation locations for winter, spring, and autumn (Figures 7, 8). The most pronounced changes were obtained for summer with precipitation increases from 20 % to 100 % in all areas, except for the high mountains. However, as there is little precipitation during that season, such increases do not exceed 30 – 50 mm by absolute value.

The abrupt decrease in precipitation at Anzob pass can be explained by a lack of data. The observed strongly positive summer precipitation trend at the Irht station can be attributed to the same reason (Figure 8).

In general, it has to be noted that a conclusive trend could not be determined over the past 15 years, especially in view of the discontinuous data series, which show considerable deviation.

Snow cover

The depth of the snow cover was measured at some stations with the help of a stable snowstake during routine observations. Snowstake measurement data obtained from nine stations for the period of 1990 – 2002 were used for a snow cover analysis. The remainder of the information has not been processed yet.

The average decade maximum, annual maximal, and minimal depth of the snow cover were calculated for a comparison with climate normals and for trend estimation (Figure 9). The average decade snow depth varies from a few centimetres in the Southern valleys of Tajikistan to 100 cm in the mountain areas. Maximum annual snow depth values vary from 20 cm in the South to more than 300 cm in the mountain passes of the Gissar range.

Snow cover thickness changes were analyzed in comparison to the average long-term value for six stations. There are no data for three other stations, because they were not functioning when reference books were being developed (before 1960).

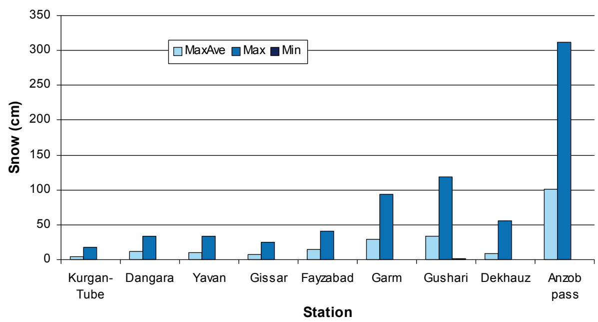

Figure 9 *Snow cover depth (average decade maximum, maximal and minimal depth for the period of observations (1990 – 2002).*
Stations are placed according to their elevation ascending above sea level.

Differences between the observed snow cover depth parameters for the study period compared to the long term normals were calculated to estimate the deviation (Figure 10). The analysis shows that the differences from the normals for average decade maximum snow depth were positive as well as negative. Therefore, no clear trend could be observed. It became evident however, that the range between absolute maximum and minimum values has expanded. No trends could be determined for Southern areas (Kurgan-Tube), however, snow depth are generally low in these locations anyway.

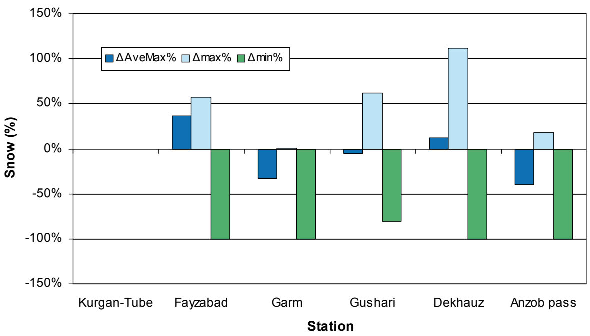

Figure 10 *Difference in snow depth between study period and long term normals in %.*

It should be noted that more data is needed to see the real picture. Such data, however, is currently unavailable due to abovementioned reasons.

Glaciation

Fresh water stored in the glaciers of mountain regions represents a crucial share of the available water resources. Glaciers are amongst the least studied fields of the geographical environment because of problems with access and other factors of high mountain areas. Before 1990, various departments and institutions had occasionally run extended research programs and expeditions. We know of several professional studies of glaciation in Tajikistan over the period of 1990 – 2005 consisting of surveys and reconnaissance field works. For example, in 2002, Dr. L. Braun headed an expedition to the lower reaches of the Grum-Grzhimailo glacier, and in the summer of 2006, a team from the National Hydrometeorological Service and International Foundation for Aral Saving conducted a two week expeditions along the Gissar range and to the Fedchenko glacier. It is doubtful whether such short-term expeditions are able to provide sufficient glaciological information to estimate glaciation change.

According to Krenke (Krenke 1982), for 20 years of intensive glaciological studies comprehensive measurements cover only 1/200 (0,5 %) of the glaciated area, partial measurements are available for about 1/25 (4 %), while fragmentary observations were conducted for 1/6 (17 %) of the glaciated area. Nowadays, studies of glacial systems should be based on indirect and distant methods using remote sensing techniques. Direct measurements should only be used to calibrate the calculations and to verify results.

The insufficiency of glacial studies is further illustrated by the fact that neither quantity of glaciers, nor the area of glaciations has been determined conclusively yet. One available source, the official glaciological publication, “Catalogue of Glaciers”, states that there currently are 8492 glaciers in Tajikistan with a total area of 8476 km², or about 6 % of the entire territory of Tajikistan (Catalogue of Glaciers of USSR, 1969 – 1980).

The atlas “Natural Resources of Tajik SSR” was published in 1983 based on satellite images. A map of current glaciation is included in this publication. The accompanying preamble states: “The map of ‘Current glaciation’ specifies all glaciers of Tajikistan with an area over 0.5 km². It was identified that the total number of glaciers with an area over 0.5 km² is not 8745 as assumed previously but 9009. The amount of surging glaciers increased from 18 to 78. The total glaciated area is 7979.2 km²”. This map had been developed by the Tajik branch of the State Centre “Nature” and glaciologists from the Department of Natural Resources Preservation and Rational Use of the Academy of Sciences of Tajik SSR.

Thus, just these two official publications provide three different pieces of information on the amount of glaciers and their areas. Furthermore, the provided values on glaciation differ substantially from each other.

The world atlas of snow and ice resources (1997), based on information available before 1980, was published in 1997. This Atlas refers to the Fedchenko glacier and many other glaciers as surging type glaciers. The majority of the data for all mentioned publications was obtained from space images and air photos.

Nowadays, new technologies including remote-sensing become more and more important. This minimizes the access problems and expands the area that can be covered. However, air photographs and satellite images should be deciphered and interpreted with due care, attention, and professionalism since considerable errors can occur in the process both through the fault of researchers.

The latest generalization and analysis of glaciological data from Pamir-Alay was done by A. Schetinnikov (Schetinnikov 1998). He estimated glaciation changes from 1957 to 1980 (23 years), and gave detailed description of this glacial region. It is, however, not clear how glaciers have changed as a result of climate change in the 25 years since then as there were no regular studies conducted since the early 90-s.

According to Schetinnikov (Schetinnikov 1998, p.p. 184 – 185), the initial period of research, the years from 1957 – 1959 (Kotlyakov 1968), were quite snowy . The studies were based on air photo images (API) and, towards the end of the study period, on satellite photo images (SPI). There were photo interpretation errors which made it difficult to identify glacier mar-gins covered by snow especially in the snow rich initial phase. In the following years, the snow cover disappeared from the upper parts of the mountain ridges due to precipitation de-crease and the rock margins of glaciers were exposed. Thus, the upper glaciation border re-ceded. The same phenomenon could be observed in the lower reaches of the glaciers. As a re-sult, a reduction in glaciation area was observed. This is one of the obvious factors.

There are other reasons influencing the accuracy of glaciation assessment. In the course of the research expedition conducted in 1957 – 1958 under the Programme of the International Geophysical Year (IGY), the borders of Fedchenko Glacier were studied. Based on results of these studies, S. Chertanov wrote: "… Rapid advance of the glacier in 1910 – 1913 was caused not by meteorological processes but by shifts of ice and snow masses in firn area from steep slopes as a result of an earthquake in the Sarez locality on the night of 19 February in 1911, which accelerated the glacial movement speed. This might be true for other glaciers in the region as well. Glacial masses, which advanced to the wide part of the valley by 800 – 1000 m, started fading because in the following years movement speed dropped significantly, i.e. showed values adequate to sustainable (permanent) meteorological processes, taking place in the glacial equilibrium line …". He also notes: "The glacier margin should retreat to the narrow part of the valley (behind the crossbar) at an elevation of 3150 – 3200 m a.s.l., where it becomes more stable as its losses are replenished annually by melting glacial masses". It is known, that at present the glacial margin has not reached this level yet.

There is no doubt that the same event affected other large Pamir glaciers, including the second largest glacier, Grum-Grzhimailo. The strong earthquake which happened on February 19, 1911 influenced the entire Pamir and has doubtless triggered the advance of many glaciers. The event was also the reason for the formation of the Usoy dam and Sarez Lake. But as the region had not been studied at that time, researchers identified the position of glaciers that had already advanced, and took their margins as the norm in the following years.

M. Hauser (Braun & Hagg 2003) selected several sources to compare the changes of the lower margin of Grum-Grzhimailo glacier. First maps of this region, developed by R. Finsterwalder, and space images obtained in different years were used for a reconstruction of glacier position (Figure 11). A comparison of data shows that the glacier has retreated more than one kilometre from 1928 to 1990. However, this cannot conclusively prove glacier degradation since, in all likelihood, the Grum-Grzhimailo glacier had also experienced the same shift of ice in 1911 as the Fedchenko glacier, and it could be argued that, at present, the advanced mass is melting. This, however, is only an assumption as the Grum-Grzhimailo glacier has not been studied in detail yet. Only one reconnaissance expedition to the region (headed by Dr. L. Braun in 2002, as was mentioned before) has been conducted so far.

In 1980, during the expedition to the East Pamir glacier No 266 – Gurumdi (South-Alichur range), several panoramic photos were taken. The glacier, which has an area of 0.4 km² according to API for 1947, or 0.5 km² according to API for 1948 (it is not known whether the different values are due to a difference in actual glacier size or just an inaccurate interpretation) is not strongly affected by solar radiation as it is located on a North facing slope. Rather the glacier balance depends mostly on air temperature and precipitation. Photographs were taken from the opposite slope at an elevation of 4850 m a.s.l. In August 2001, the glacier was visited again and new photographs almost from the same point were taken (Figure 12).

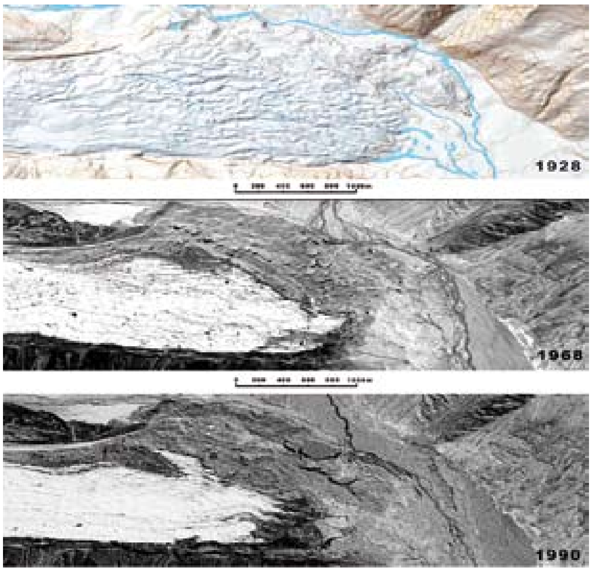

Figure 11 *Comparison of the lower margin of the Grum-Grzhimailo glacier in different years. Data of 1928 (R. Finsterwalder), 1968 (satellite image Corona), and 1990 (satellite image TFA 1000). Figure produced by M. Hauser, personal communication.*

A preliminary comparison of the photos indicated that the glacier had degraded significantly. But when dates and images were carefully compared and studied, this finding proved to be wrong.

The first photo was taken on July 26, 1980, and the second one on August 16, 2001. The large photos of 1980 show that the glacier tongue was rutted by cavities and had snow on it. As Mid-August is the final ablation period in this area and considering the

Figure 12 *Comparison of margins of Glacier No 266 (Gurumdi) based on photograph of 1980 (red outline) and 2001 (photo). Photo taken by A. Finaev.*

low snowfall amounts of the previous winter, it can be concluded that in August of 2001, when the photo was taken, the snow had completely melted and the glacier showed its real dimensions. Visual observations made in the 1980-s and data from the Catalogue of Glaciers10 based on air photography of 1947 show that "the glacier's lower margin has two branches with the right one reaching the border of glacier No 265". The photos of 2001 confirm this statement. In the right bottom part of the photo the margin of glacier No 265 can be seen.

This proves the ambiguous assessment of glaciation changes based on air photos. It is obvious, that in addition to climate changes, there are other reasons influencing glacier margin positions. Thus, it would be, at least, incorrect to talk about glacial degradation in Tajikistan due to global warming without carrying out further fundamental studies and regular observations in this field. The emphasis should be put on remote-sensing methods, confirmed by field work research of some typical glaciers.

River runoff

The data from 5 hydrological posts (h/p) measuring streamflow and representing different regions were selected to study the hydrological situation. It should be noted that these posts also had observation gaps within the researched period. Despite this fact, we may assess water discharge trends and changes with regard to average climate values (State Water Cadastres 1987) based on the information available.

The Kzylkishlak post on the Syrdarya river represents the typical hydrological regime of Northern Tajikistan. For the past 15 years, the post showed a constant increase of average annual water discharge from 500 to 800 m³/s (Figure 13).

It should be noted, that after 1999 there are data available for 2003 only at Kzylkishlak post. The lowest growth trend was observed at the Zeravshan river (Dupli h/p, data till 1997 with interruption in 1995 – 1996) with water discharge increasing from 170 to 220 m³/s.

In the Gissar range and in the Pamir mountain areas, water discharge trends could not be observed (Dagana and Khorog h/p respectively). Data for these posts are most complete, though there still are some gaps – one year in Dagana and three years in Khorog.

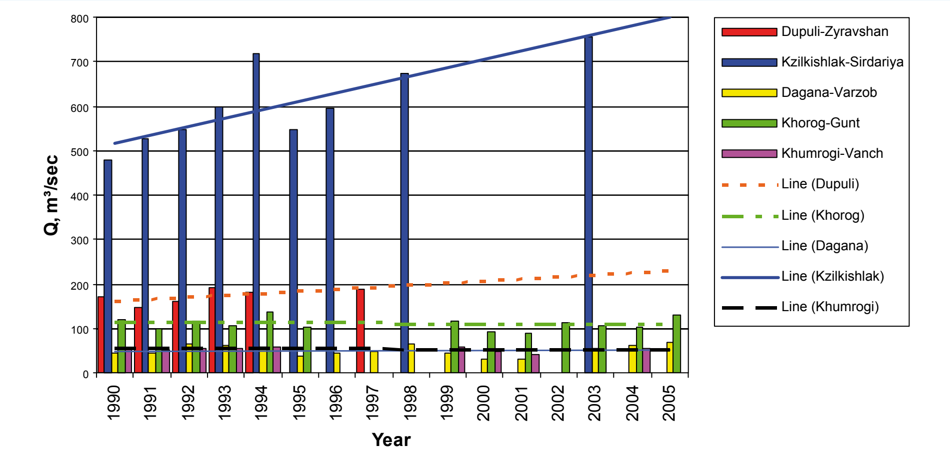

Figure 13
Average annual water runoff in m³/s

To enhance the runoff monitoring, it is necessary to improve the activities of existing posts and to reinstate inactive stations, especially at outlets. For example, it would be important to reactivate the Tigrovaya balka post located on the downstream portion of the Vakhsh river, because its data could be used for an assessment of the water discharge of the entire Vakhsh basin.

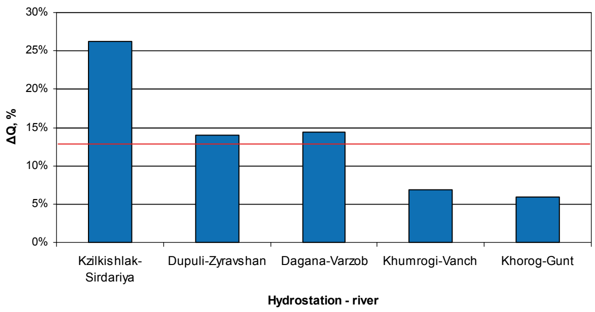

Figure 14 *Average water runoff trend for 1990 – 2005 in %.*

Conclusions

The hydrometeorological situation in Tajikistan is monitored by the National Hydrometeorological Service (NGMS) through a network of stations and posts. Over the period from 1990 – 2005 the amount of operating observation points has changed significantly, resulting in the discontinuity of many data series. Most information is available on paper, as documents and materials have been received from stations for more than 15 years. Presently however, the NGMS is unable to process this extensive information and does not convert them on to magnetic or other database media.

The study of data supplied by 16 stations from various regions showed that air temperature increase continued at the rate of 0,039 °C per year on average. The temperature increase rate decreased with elevation. The highest air temperature increases were observed in winter (0,093 °C/year) and autumn (0,05 °C/year), while the increase in spring and summer was insignificant with values of 0,024 °C and 0.013 °C respectively. Average annual temperature fluctuations were periodical. Three peaks of maximum and two peaks of minimum values can be identified within the study period (1990 – 2005).

For precipitation, a five-year cyclic recurrence becomes obvious especially at the stations that have the highest precipitation amounts. Maximum annual precipitation totals are about twice as high than minimum values. We may note that in winter and spring precipitation exceed the norm by 20 % to 50 % and in summer and autumn by 70 % to 100 %. There was no trend in long-term average annual precipitation change within the researched period (1990 – 2005). The average annual precipitation over the study period using all stations was 18 % higher than the normal. This suggests that the increase of precipitation above the climatic norm must have taken place before 1990.

To study the depth of the snow cover, we used data supplied by nine stations. However, only six of those could be compared to a long term normal. The analysis shows that the average decade snow cover thickness seems to be increasing with elevation from a few centimetres in valleys to one meter in the mountains with absolute maximum values reaching three meters. There was no trend revealed in the analysis of snow cover thickness change.

No regular glaciological studies have been done to estimate glaciation changes for the research period. The most recent publications are based on data obtained before 1980 – 1990. In the last 15 years, there were several short-term reconnaissance and survey field studies but they did not provide reliable glaciological information. There is some evidence of a reduction of the glaciated area, but it is too early to give a conclusive assessment. Factors impacting the assessment of glaciation parameters include air and space image interpretation errors, the date of image recording, the melting of surging glaciers after their large advances, and the temperature increase as a result of global warming.

The analysis of average annual water discharge was based on data supplied by five hydrological posts and showed that, for the selected period, annual water discharge increased in the rivers of Northern Tajikistan: Syrdarya river – 19 m^3/year, Zeravshan river – 4.6 m^3/year and Varzob river – 0.2 m^3/year. In the Pamir rivers – Gunt and Vanch – the average water discharge rate decreased by 0.28 and 0.33 m^3/year respectively. However, average annual water discharge for all rivers exceeds the long term normal of 13.5 % ranging from 5.9 % at Gunt river to 26 % at Syrdarya river (Figure 4). As the precipitation exceeds the normal during the same period by 18 %, it is plausible to assume that the annual water discharge increase occurs basically as a result of precipitation increases.

Thus, in order to get a true assessment of the hydrometeorological changes, it is necessary to process the available archived observations for the last 15 – 20 years and to improve the effectiveness of the entire net of stations and posts. Only then a forecast of the climatic characteristics and glaciation changes in the region becomes feasible.

Acknowledgements
Our acknowledgements are to Dr. Anil Mishra on behalf of UNESCO for the organization of the conference and the discussion of the subject, as well as to the top managers and staff members of the National Hydrometeorological Service of Tajikistan for the supplied data.

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Hydrometeorological monitoring system in Uzbekistan

Gleb E. Glazirin

Economic activities and the existence of people in Central Asia depend entirely on the presence of water originating from mountainous areas as a result of the melting of seasonal snow covers, glaciers and, partly, precipitation. Therefore, the understanding of runoff producing processes, as well as the monitoring of the climate and water resources is a vital task for all the countries of the region. The system of supervision, which had been well organized during most parts of the last century, has considerably suffered during the last 10 – 15 years, after the disintegration of the USSR, which also resulted in a decay of the uniform hydrometeorological service. Before that, several generations of scientists had already been investigating the basic hydrometeorological processes taking place in the region. Forecast methods were developed, and an inventory of glaciers, lakes, and rivers was compiled. Such cumulative knowledge allows the prediction of the effects of probable natural or anthropogenic climate changes on the water resources of the region. This review contains some brief data concerning the history of hydrometeorological and glaciological observations in the region, their current state, and some tendencies of changes in the observed rivers, climate variables, snow covers, and glaciers.

Introduction

Four main periods can be distinguished in the course of meteorological and hydrological observations in Uzbekistan.

The first period began with the organization of Tashkent's astronomical and physical observatory in the 1870s. The first meteorological stations and posts and a special hydrometric division were established then. The division combined hydrometric and meteorological observations into one organisation. At the same time the first elementary research of mountain glaciers was carried out.

The second period extended from 1918 – 1945 beginning after the revolution of 1917. During this period the centralized weather service was established, and some research connected with national economic interests was conducted. A network of stations, including high-mountain locations, was established and the volume of observations considerably increased.

The third period can be called the post-war era. The hydrometeorological system of Central Asia received new modern equipment and computer facilities and the network of stations was extended. By the end of this period there was a maximum amount of hydrological and meteorological stations and posts. Aerial observations were widely used for research of the snow covers and glaciers during this period.

At last, the fourth period can be described as a time of fast degradation of the hydrological and meteorological observation system with a considerable reduction in the number of stations (especially in the high-mountains). This trend started after the disintegration of the Soviet Union in the beginning of the 1990s. Unfortunately, this sad period is still going on today.

One of the consequences of the disintegration of the Soviet Union into several smaller states are problems with the data exchange between the weather services of the newly formed states mainly due to commercial reasons amongst others. Similar to all new countries formed after the end of the Soviet Union, Uzbekistan's network of meteorological and hydrological observation points has suffered substantially, although less than in other countries of Central Asia.

At the same time Uzbekistan is at a great disadvantage concerning the reception of essential information related to its water resources as practically all the zones supplying water to the rivers of Uzbekistan are situated outside the country. Only 9–10% of the consumed water comes from precipitation and the melt of glaciers from within the country. This is the reason why the mentioned problems with data exchange are especially important for the national economy of Uzbekistan (Water resources of USSR and its utilization 1987; U. Ivanov, unpublished data).

The current state of the existing observation network is described below. The observations of climate variables, river discharge, snow cover, and glaciers (situated mainly in Uzbekistan, but also in other parts of Central Asia) will be considered.

Climate Monitoring

Description of the climate monitoring stations and their changes over the last 15 years

The current observational network of the weather services of the states of Central Asia is not capable of satisfying the information requirements of all users, including the requirements of these very services to produce effective weather forecasts and for their various other commitments. The 1980s were the heyday of that network, but it has degraded extensively since the beginning of 1990s. The number of active observation stations for this period is listed in table 1 (Unified Regional Report 2004).

Table 1 Number of meteorological stations in Central Asia for the past 20 years

State	Number of meteorological stations		
	1985	1996	2004
Uzbekistan	91	75	78
Kyrgyzstan	95	62	31
Tajikistan	64	51	47
Turkmenistan	51	51	48

This table needs some further comments. First of all, the data concerning Turkmenistan is somewhat doubtful, as it is known from other sources that its meteorological network has declined. It should also be noted, that high-mountain stations, which are hard to access, have suffered the most. This is especially unfortunate as the data provided by such observation points are very important for hydrologic studies.

The problems of the observational network are not limited to a reduction in the amount of stations, but also include the absence of instruments, equipment, materials, and spares. These problems caused a series of stations, which were not closed entirely, to reduce or completely stop their exploration. In some cases, especially at isolated and hard to reach stations, observations were affected, but this information was not reported immediately to the hydrometeorological services because of a lack of communication facilities. This indicates that the development of a network is not a priority task right now, but, rather, the preservation and upgrading of the equipment at existing stations should be the first step to solve the problem.

The major role in the maintenance and development of a meteorological and hydrological network in the states of Central Asia belongs to a group called "Swiss support of hydrometeorological services of the Aral sea basin" (former "Swiss mission across the Aral sea"). In the near future the reconstruction and re-equipment of a considerable number of stations is going to be conducted. The observation points which are most important for an increased accuracy of meteorological and hydrological prognoses will be renovated first. Switzerland should cover up to 85–90% of the relevant expenses.

Direct access of users to the data is currently limited as a considerable part of the databases is still exists only on paper. Information is granted according to special agreements or single inquiries. The procedure is, as a rule, not free of charge.

Recent changes of climate

The quantitative weather features of a single year or of a small time interval differ from average perennial (climatic) characteristics taken for 30 or more years. According to the data observed at stations with a data record of more than hundred years, there are also differences between long lasting periods (epochs). Such inter-annual and inter-periodic differences are called "variability (oscillations, fluctuations) of climate". If the average climatic characteristics of consecutive time intervals are systematically decreasing or increasing, it can be called a “climate fluctuation”. The concepts of “change” and “variability” are relative and depend on the temporal scale.

The reasons of climate change and oscillations can be subdivided into natural (change of Earth motion, activity of the Sun, change of the general atmospheric circulation etc.) and anthropogenic ones. Examples of anthropogenic causes are: the urbanization and melioration (for instance, the change of summer air temperature and augmentation of humidity in the Hungry steppe and the Fergana valley). For the past 20–30 years the increase of greenhouse gases in the atmosphere can also be added to the list. It should be noted, that the first two causes mainly influence the local climate, while the last one affects the global climate. It is important to mention that the inherent considerable variability of climate doesn’t permit, in many cases, a confident quantification of the anthropogenic component of a general pattern of climate fluctuation.

Further complicating an evaluation of long-term climate fluctuations are change in instruments, measurement procedures, and meteorological station environments. For example, the meteorological station called “Tashkent” was established in 1873 in the suburbs of the city. However, it is currently situated practically in the center of the city. During the last 130 years the guard system of a lot of precipitation gages, the construction of weather boxes, and the mode of observation has changed. All the above mentioned factors affect the measurement results and, hence, the reliability of the evaluation of long-term climate fluctuations

An analysis of perennial climate fluctuations was conducted in a study by Spectorman and Nikulina (2002). Data from 50 meteorological stations within Uzbekistan (situated in different physiographic and anthropogenic conditions) were averaged for an objective evaluation of climatic changes on Uzbekistan’s territory. The stations were selected on the basis of an analysis of duration, continuity, and homogeneity of the observation series.

Figure 1, first published in the cited study, shows the course of anomalies of average annual air temperatures relative to a long term average (1961–1990). It becomes evident, that the temperature has been increasing continuously since 1933.

The modification of annual precipitation for the same period is reflected in Figure 2. No trend can be seen.

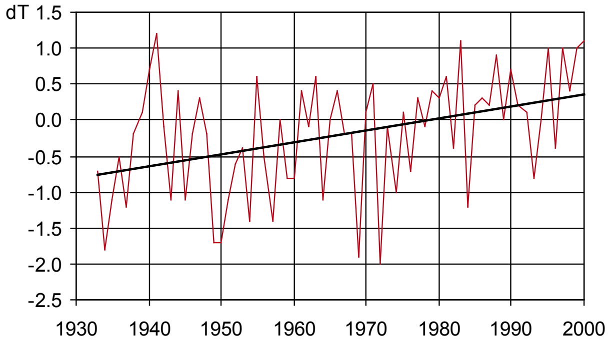

Figure 1 *Average anomalies of average annual air temperatures compared to the long term averages (dT, °C), for selected stations of Uzbekistan (Spectorman & Nikulina 2002).*

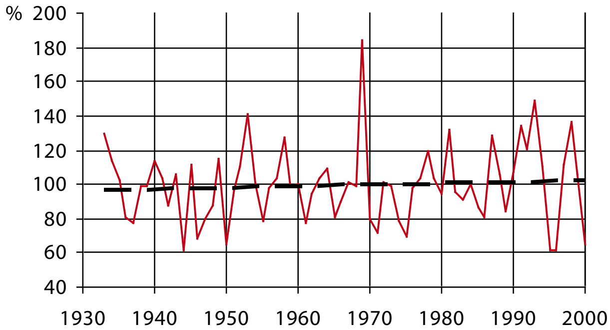

Figure 2 *Perennial course of annual precipitation amounts, averaged over selected stations compared to the 1961–1990 average in percent (Spectorman & Nikulina 2002).*

The perennial course of average annual air temperature, registered at the station with the longest record in this region (Tashkent) is representative for the region: a continuous increase of annual air temperatures has been observed up to the present (Figure 3). Figure 4 shows that this growth is caused mainly by increasing winter temperatures. At the same time precipitation amounts varied around the average (Figure 5). A slight precipitation increase evident in the figures can be attributed to a change in measurement technique. The more pronounced increase in winter precipitation, reflected in figure 6, can be explained by the same reason.

To compare these values the same trend analysis was done for the average annual temperature at a station

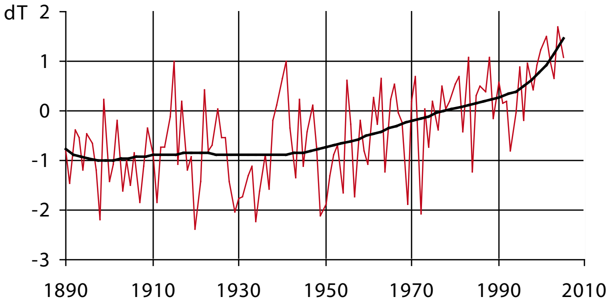

Figure 3 *Perennial course of average annual air temperature divergence (dT, °C) from the long term average (1961–1990) at the Tashkent meteorological station*

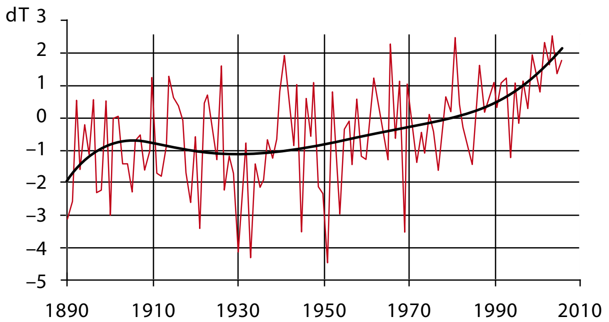

Figure 4 *Perennial course of average air temperature divergence in the winter season (dT, °C) from the long term average (1961–1990) at the Tashkent meteorological station*

called Oygaing. This station is located at an elevation of 2150 m a.s.l. in the Psken River basin in the Western Tien Shan (Figure 7.). At the present this station is the highest mountain station in Uzbekistan. It becomes evident that the temperature increase in Oygaing is not as pronounced as in Tashkent. At the same time, figure 8 again indicates that the change of temperature mainly occurs during the winter period.

It would be rather interesting to also analyze the air temperatures and precipitation data from the station called "Fedchenko Glacier", situated at an elevation of 4160 m a.s.l. However, this high mountain station, the highest in Central Asia, has stopped working in the early 1990s. A significant increase in precipitation was observed at that station from the mid-1980s until the 1990s. At the same time the summer temperature determining the thaw of glaciers and the snow cover practically did not increase. An automatic meteorological station was established there several years ago, but the measurement data remains hard to access and, in addition, no parallel explorations using both, old

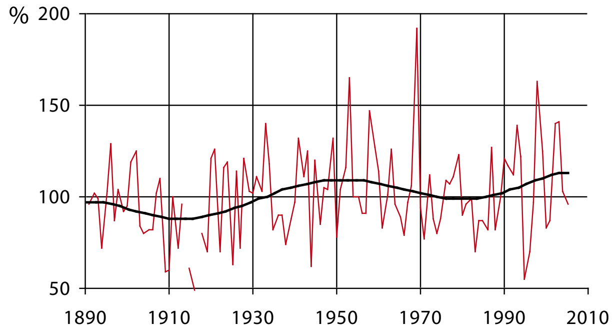

Figure 5 *Perennial difference of annual precipitation amounts from the long term average (1961–1990) at the Tashkent station in percent*

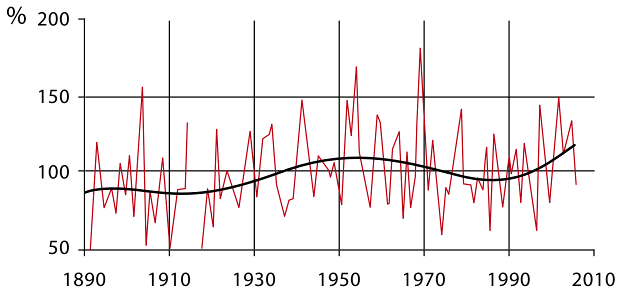

Figure 6 *Perennial difference of winter precipitation amounts from the long term average (1961–1990) at the Tashkent station in percent*

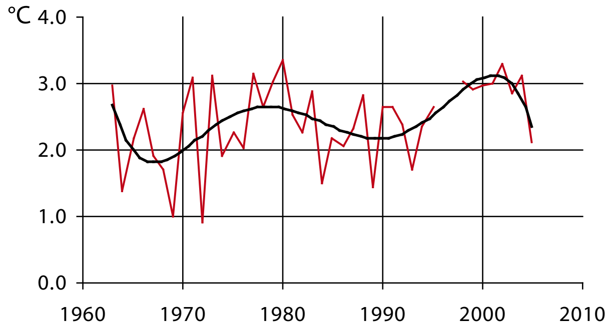

Figure 7 *Trend of average annual air temperature at the Oygaing station.*

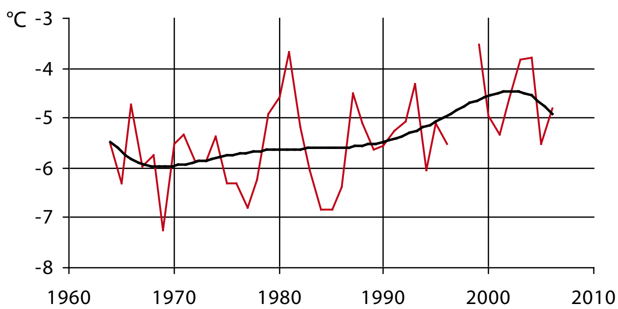

Figure 8 *Trend in winter temperature at Oygaing station.*

and new equipment, was conducted. Thus it is impossible to determine data continuity and therefore long-term trends of metrological parameters.

Overall, the available data allows the conclusion, that the average annual air temperature increases and that this increase is mainly caused by higher winter air temperatures. Furthermore, according to the available data, the temperature increases in high-mountain areas are not as pronounced as on the plains. The annual precipitation amount seems to remain virtually constant with maybe some slight increase at all elevations. However, it should be noted again, that this long-term growth could also be explained by an alteration of the measurement methods.

It is necessary to emphasize again, that the destroyed network of mountain meteorological stations does not allow the accurate evaluation of the modification of meteorological parameters in the most interesting (from the point of view of river flow formation), high-mountain areas.

Forecast of permanent climate modifications

Today, climate change forecasts are mainly based on general circulation models (GCM). Predictions of atmospheric greenhouse gases (such as carbonic gas, methane, nitrous oxide etc.) concentrations are also taken into consideration. Various scenarios of climate changes are known reflecting the considerable role of anthropogenic factors in the formation of the mentioned gases (Climate change 2001). According to several projections global air temperatures will rise by 1.5 – 5.8 °C in the 21st century.

The special report concerning possible scenarios of greenhouse gas emissions (IPCC Special Report on Emission Scenarios 2000) contains information on several new scenarios. The so called B2 scenario has been declared the most appropriate for Uzbekistan. It describes a world where basic attention is given to local decisions concerning economic, social, and ecological stability, along with a constantly growing population. As a rule, results of GCM's are provided at a low resolution of about 300 × 300 km and more. This does not allow their direct application in small territories. Therefore, it is necessary to adapt the results for those areas. The first results of studies looking particularly at Uzbekistan were published by Spectorman & Nikulina (1999), and by Spektorman & Petrova (2006).

The results are briefly discussed in the following. The period of 1961 – 1990 was chosen as base period, as was recommended by WMO. The studies concluded, that the air temperature will increase throughout all seasons by 2050, but there will be slight intra-annual differences. The winter (December to February) temperature increase was predicted to be 2.5 – 3.0 °C, while summer increases were projected to be 1.7 – 2.2 °C. The annual precipitation amount was projected to increase slightly, mainly due to a 10 – 20 % winter growth while summer precipitation will remain almost constant. Unfortunately, it is not possible to make predictions separately for low lying and mountain areas.

Monitoring of Snow Cover

A modern network of stations for the observation of snow covers

In general, the data related to snow cover in mountains, which represent the major runoff source for the rivers of Central Asia, is collected mainly by hydrologists. The first regular ground snow surveys started in 1923. The establishment of operational hydrometeorological stations in high mountain areas became a major step in the creation of a system to explore the snow cover in mountains. First of all, these stations allowed the implementation of regular snow surveys in deep mountain valleys and in other places which had been inaccessible up to then. The following tasks were included in the work of high-mountain stations: daily observations of snow cover height at a particular snow pole, and every ten days measurements of snow height and snow density along a snow course of 1 km length. At the same time, regular snow surveys were organized in 24 river basins at 737 locations. Precipitation measurements were also conducted using integral precipitation gauges.

In the early 1960s, remote measurements of snow height at snow poles from helicopter were established in high-mountain areas, which are otherwise inaccessible in winter. This method was applied practically in all mountain areas of Central Asia (Iljin 1961). The height of the seasonal snow line was also simultaneously determined. There were 51 snow survey courses and more that 100 distance rods in Uzbekistan by the middle of the 1980s. The use of aerial snow height measurements made it possible to reduce the number of dangerous snow survey courses although that method was still used albeit in a shortened form. In 1975 Sanigmi in cooperation with VNIISHIM

(Obninsk) started to explore the possibility of measuring the snow water equivalent of mountain snow covers using the method of gamma ray shooting from helicopters (Getker et al. 1978). Subsequently, this method was widely applied in the mountains of Central Asia and provided very valuable information. However, all these observations ceased mainly due to their high cost.

Satellite pictures have been used in Central Asia since the beginning of 1970s to estimate the snow depths in the country. The regular stream of such pictures is currently the most valuable initial information regarding snow cover. Straight snow cover measurements have been conducted as a part of the ongoing research directed at optimizing the observation network, while more complex measurements using various research methods were carried out mainly for hydrological forecasts (Denisov, 1963; Getker & Shentzis 1972; Getker, 1996 and many others).

As a result of the disorder and disintegration of the hydro-meteorological services of the USSR, the network of snow measuring points has suffered even more extensively than the network of meteorological stations. The consequences of this process can be seen in table 2 (Unified Regional Report 2004). It becomes evident, that the snow measuring network has been catastrophically reduced. The main areas of concern regarding this degradation is in Kyrghyzstan and Tadjikistan where the headwaters of practically all rivers of the region are located. It is obvious that the reconstruction of the ground snow-gage network and the creation of a system to monitor the headwater streams is one of the most important tasks for the region. This would, undoubtedly, raise the quality of river flow forecasts.

There is hope, that the situation can be corrected during the realization of the project called “the Swiss support of hydrometeorological services of the Aral sea basin”.

Results of research into the inter-annual variability of the snow cover, its characteristics and its spatial distribution in an area of high mountain relief
The long-term analysis of the snow cover in the mountains of Central Asia allowed scientists to obtain quite detailed information on its characteristics. They are summarized in a number of articles and, especially, books (Sanigmi, Tashkent 1988; Tsarev 1996).

Table 2 Change in the ground and aerial snow measuring network in Central Asia in recent years (Number of river basins where air supervision, using distance rods, is conducted are marked in brackets)

State	Quantity of snow measuring routes (basins with air supervision)		
	1985	1995	2004
Uzbekistan	18 (18)	2 (7)	2 (7)
Kyrgyzstan	15 (13)	0	0
Tajikistan	28 (12)	2 (0)	7 (3)

Methods and diagrams of average long-term dates of formation and disappearance of the snow cover, the duration of a steady snow cover, maximum snow depths, and the inter-annual variability of these characteristics for all elevations in all mountain areas of Central Asia are listed in “Methodical recommendations”. It is not feasible to list all the data contained in this book here. Instead, only the general trends will be mentioned, since they are uniform for all mountain territories of the mid-latitudes:

- Steady snow cover duration and maximum snow depths are increasing with elevation;
- The higher the given territory is located, the earlier a steady snow cover settles in autumn and the later it disappears in spring;
- The average long-term top elevation of a persistent winter snow cover goes down to about 2000 – 3000 m in the south of territory and up to 1200 – 1500 m in the north ones.
- The inter-annual variability of the listed snow cover characteristics slowly increases with a reduction of maximum snow water equivalent, and then quickly increases when approaching a zone with an unstable snow cover.

Recent changes in snow cover characteristics
The number of days with a ground snow cover is not the best characteristic to describe snow cover conditions, but it is the most reliably determinable. The change of this variable at the Tashkent meteorological station is shown in figure 9. The negative trend is quite clear to see: for approximately the last 80 years, this parameter has decreased from 60 down to 30 days a year. Figure 10 shows the same parameter for the mountain station at Oygaing. Again a decrease in the

number of days with a snow cover can be detected. Taking into account, that the annual and winter precipitation remained fairly steady or even increased slightly at these stations, warmer winter air temperatures are the most likely reason for this reduction.

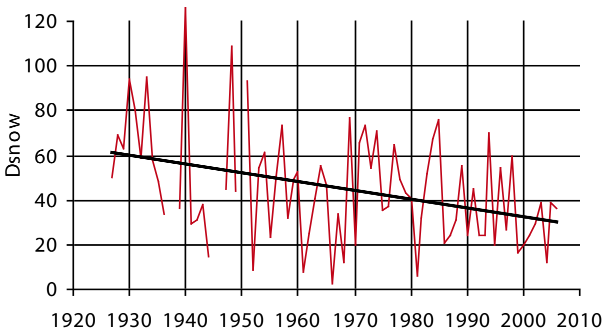

Figure 9 *Change of the number of days with snow cover (Dsnow) at the Tashkent station.*

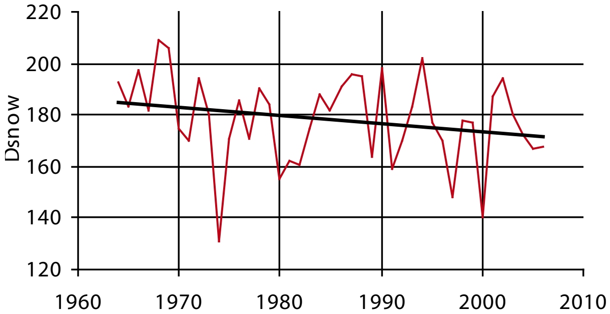

Figure 10 *Change of the number of the days with snow cover (Dsnow) at the Oygaing station*

Unfortunately, there are no long-term data about maximum snow water equivalent of the snow cover for the stations at our disposal, but it could be expected, that this parameter varies not as strongly at mountain stations since the decrease in the number of days with a snow cover at these stations is caused mainly by higher air temperatures during snow cover formation and melt.

Change of snow cover characteristics for projected future climate conditions

Obviously, projections of long-term climate changes should be the basis for such forecasts. But in our opinion, such projections are not reliable enough at the present. It could be argued, that the changes in snow cover characteristics depend on the amount of snow received: the less snow a territory gets, the more sensitive the snow cover characteristics will react to climate change. Therefore, predictions of reaction of the snow cover to climate changes should be made separately for each concrete place and model projection.

The statistical method based on the application of the theory of turns and statistical tests (Monte Carlo) (Glazirin 1997) is quite universal and flexible. It allows the determination of the time of formation and disappearance of a snow cover, its duration and maximum depth in any location and for all climate projections (Reports of NIR, 1999).

An application of this method shows the following main tendencies:

- An increase of winter temperatures results in a reduction of snow cover duration period (see the examples of Tashkent and Oygaing considered above);
- In places where snow cover is currently insignificant, it can become unstable with the increase of temperature;
- The maximum snow depth is less sensitive to an increase of winter temperatures at high elevations, but, naturally, it is sensitive to an increase of precipitation amounts;
- With increasing winter precipitation there is a shift of the date of maximum snow depth towards the spring.

Table 3 shows the change in the number of winters with a steady snow cover and the duration of a steady snow cover at the station Dukant, located near Tashkent at an elevation of 2000 m a.s.l.

Table 3 Fraction of winters with a stable snow cover (numerator) and duration of a stable snow cover (denominator) at Dukant for changing climatic conditions

Changes		ΔT, (°C)			
		0	+1	+2	+3
	−15	1/102	0.76/57	0.04/37	0/-
Δp,					
	0	1/111	0.88/61	0.10/40	0/-
(%)	+15	1/115	0.96/67	0.16/40	0/-
	+30	1/120	0.99/75	0.22/42	0/-

Monitoring of Glaciers

The research of glaciers in Central Asia started in the second half of 19th century. The first travellers crossing vast mountain ranges discovered powerful glaciers, noted their position on maps, and made the first primitive sketches of the glacier fronts. This created the first authentic picture of the distribution of glaciers. The following stage of glacier studies in the region was characterized by regular research expeditions to the most remote areas of the Tien Shan and the Pamir. The role of the Tajikistany-Pamirian expeditions and studies carried out during the International Geophysical year was especially great in this. The participation of foreign, mainly German, scientists also played a big part in these studies.

The publication of the multivolume USSR glaciers catalogue represented a considerable stage of glacier research. Data from all glaciers larger than 0.1 km² in size are collected in that publication. The catalogue is the basis for further estimation of glaciation change.

Modern system of glaciation monitoring
There are some basic methods used to monitor the status of glaciers:

- Periodic geodesic survey of the glacier fronts. Towards the mid-1980s such surveys were carried out in Central Asia on more than 60 glaciers. This enabled a determination of glacier changes in practically all mountain areas of the region. Such surveys are not conducted presently.
- Summer expeditionary research into glacial flow, balance, weight, and dynamics, as well as the meteorological conditions in which the glaciers are existing. Such studies were not conducted after the disintegration of the USSR.
- Regular all-year-round activities at several glaciological stations. The main stations are: the Tuyuksu glacier in Kazakhstan and the Karabatkak and Abramov's glaciers situated in Kyrgizstan. The latter one, in spite of its geographic location, is researched by the specialists from SANIGMI (Tashkent). The station on the Karabatkak glacier stopped working at the end of the last century; and the station called 'Abramov's glacier' was blown up by terrorists in 1998. This is a considerable loss for global glaciology because of the great importance of the data collected there for many years (Pertsyger, 1996; Glazyrin et al. 1993). There is no hope either for a restoration of these stations or for the organization of a new similar exploration points.
- Periodic satellite images. These images can be used to observe the pulsations of glaciers and to provide data on the reduction of the glaciated area. It is practically the only type of glaciological monitoring, carried out presently. However, it is necessary to note, that the reliability of glacier mapping using such images is not too great, especially when trying to determine the lowest glacier line due to ablation moraines, which often cover the tongues of glaciers. Nevertheless, it is, nowadays, practically the only source of information regarding the status of glaciers.

Current glaciated areas in comparison with the data of the first glacier catalogue. Overall and spatially distributed degradation rates of glaciers and glaciations
The first Catalogue of glaciers covered all ground glaciers of the former USSR. Its creation was a significant event in which many territorial and republican hydrometeorological services and also a number of institutes of the AS of the USSR participated in. It would be very expensive and difficult to repeat that work in its entirety. However, it is possible to conduct this kind of explorations for several larger regions. It is necessary to emphasize the work of A.S. Schetinnikov. Using aerial surveys from the 1980s he reproduced the inventory of glaciation for all Pamir-Alay highlands and, additionally, for some river basins of the Tien Shan. This is very important because it is the territory where more than 40 % of the glaciers of the former USSR are concentrated. Unfortunately, the results of this work have not been published. However, on its basis, the author published two books (1997, 1998), containing data on the current state of the freezing processes of the region's river basins (as of 1980), and about their changes for the period from the time of the aerial surveys used for the first catalogue until 1980. Data on the change of the glaciated area of the Pamir and Gissar-Alay are shown in table 4. Values for 2005 were estimated with some inaccuracy, assuming that that reduction rates remained constant until today.

Thus, if our calculations are correct, the area of glaciation of the Pamir was reduced by approximately a quarter over the last 50 years, while the glaciated area in the Gissar-Alay mountain system decreased by approximately a third. A similar picture was observed in other areas of Central Asia (Vilesov & Uvarov 2001; Seversky & Tokmagambetov 2005; etc.).

Table 4 Decrease of glaciated area (Fg, km²) glacial area covered by moraines (Fm, km²) of the Pamir-Alay highlands and yearly changes (%)

Pamir			Gissar-Alay		
Years	Fg	Fm	Years	Fg	Fm
1961	7360	420	1957	2180	167
1980	6600	640	1980	1840	200
2005	(5770)		2005	(1470)	
% per year	0.52		% per year	0.81	

It is necessary to note, that the number of glaciers is a poor parameter for an estimation of the glaciated area, as a reduction of the glaciated area might actually cause an increase in the number of glaciers due to disintegration of large glaciers. A. S. Schetinnikov (1998) calculated the volume of each glacier using different empirical formulae and found that by 1980 the total volume of ice in the glaciers of the Pamir decreased from 559 m³ down to 466 m³ (17 %) while the ice volumes in the glaciers of the Gissar-Alay declined from 105 m³ to 88 m³ (16 %). The melt water from these glaciers drained through the Syr-Darya and the Amu- Darya. However, their annual discharge at the foot of the mountains only increased by 3 – 4 %, which is close to the accuracy of hydrometric measurements.

The following is a discussion on how glacier change rates depend on their size and location. First of all, it was found, that the higher river basins are situated, the more stable the glaciation is. The least glacier reduction was detected in the highest regions of the Pamir (Karakul River basin, according to Markans data). The ice cover of the river basins located at lower elevations was reduced much more. For this reason, the glaciation of the Pamir, which, on average, is situated at a higher elevation, decreased less than in the lower Gissar-Alay highlands. Figure 11 shows the following trends of glacier reduction velocity with glacier size in the Sokh river's basin (the South of the Fergana valley, Gissar-Alay mountains): the smaller the glaciers are, the higher the reduction velocity is. A similar picture is observed in other glacial systems. The most plausible explanation of this phenomenon was given by V. G. Hodakov. He concluded that ablation is more intensive at the edges of the small glaciers compared to the middle. This can mainly be attributed to thermal radiation reflected from surrounding slopes which are strongly heated up in the summertime. Consequently, as the ratio of perimeter length to glacier and snowfield area, as a rule, grows with decreasing glacier area, the role of "lateral" thawing is enhanced on smaller glaciers.

Furthermore, it was revealed, that glaciers situated on south facing slopes are on average more stable against climate change and are declining in size more slowly than those on north facing slopes. This is in spite of the fact that they are, as a rule, smaller. As an example, the dependence of glacier reduction on their orientation in the same region is shown in figure 12. Similar dependencies are available for several other river basins. The greater "energy of glaciation" on south facing slopes could be an explanation for this phenomenon.

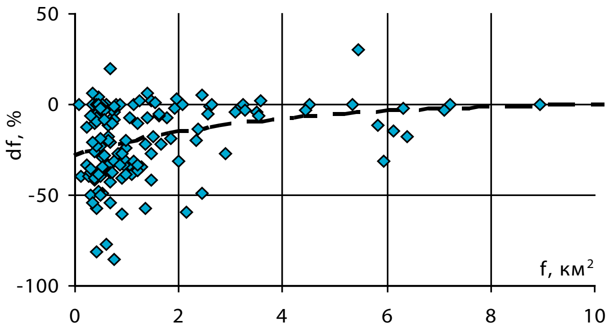

Figure 11 *Dependence of average glacier size change (df) on their initial area (f) in the Sokh River basin*

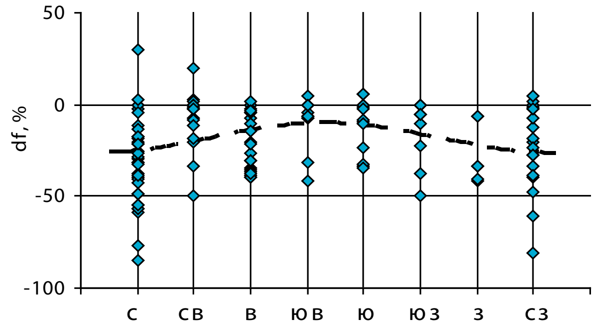

Figure 12 *Dependence of average glacier size change (df) on their location in the Sokh River basin*

The previous figures show the changes of separate glaciers for the period between two inventories. However, hydrologists need information on the overall size of the glaciated areas in whole river basins, and of its altitudinal distribution. Data on basin glaciation are published in several books (Schetinnikov 1997, 1998). Glazyrin (1991) presented a method to calculate glaciation distribution depending on altitudinal zones in basins of mountain rivers. It is based on unpublished and public information on the total area of glaciation, average height of the firn line, and the maximum grade of glaciation.

In contrast to snow cover, glaciers adapt to new climatic conditions over many years, and even decades. Glaciers are in a persistent transitive mode. Inventories fix only moments in this process. Therefore, it would be rather interesting to calculate yearly changes of glaciated area using data from the catalogues. The method for such calculations was presented by Glazirin & Kodama (2003). It is necessary to have at least three inventories of glaciers for a basin, as well as extensive data on annual precipitation and average summer air temperatures from the nearest, high-mountain, meteorological stations. The course of glaciation changes in the Yazgulem River basin (in the Pamir) is shown in figure 13. It was obtained using the results of three inventories (Schetinnikov 1998) and the meteorological data of the "Glacier Fedchenko" station, located at an elevation of 4170 m a.s.l.

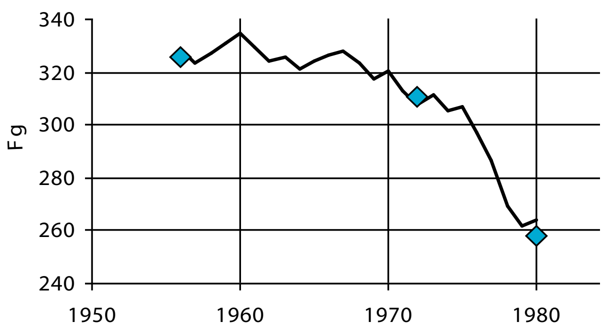

Figure 13 *Change of glaciated area (Fg, km²) in the Yazgulem River basin. The dots indicate inventory data lines show calculated results*

Overall, the glaciated area is decreasing in all mountain areas of Central Asia in the range of 0.5 – 1.2 % per year. Indeed, this process seems to have slowed down in recent years. That inspires hope that glaciers will decorate mountains for many decades to come.

Change in mountain glaciation in view of probable climate changes

It is obvious, that the glaciation of rivers basins depends both on characteristics of relief as well as on climatic conditions. It is known, that an integrated climatic parameter for high-mountain areas is the elevation of the firn line (Tronov 1966). As the relief of basins can be assumed to be virtually constant, glaciation changes should be influenced mainly by climate changes. If the climatic conditions responsible for the supply of glaciers improve (increasing precipitation and decreasing air temperatures) the firn line goes down, and glaciers are increasing in size. The reaction of glaciers to climate changes (balance of weight) can be calculated using mathematical models of glacier dynamics. However, all these models demand extensive input data, which can only be collected for individual, well investigated glaciers. Taking into account that there are thousands of glaciers in the mountains of Central Asia, an analysis of all glaciers is not feasible. The solution is to estimate changes of the entire glacial systems (sets of glaciers in large river basins).

It has been shown (Glazyrin 1985), that changes of the firn line altitude (dZf) can be calculated with the formula:

$$dZf = -1/E\cdot[p\cdot ab(Ts(Zf) - ab(Ts(Zf) + dTs)]$$

Where: ab(Ts) is the annual specific ablation on a glacier, which is dependent on average summer air temperature Ts in the well-known ratio established by A. N. Krenke (1982) and V. G. Khodakov (1965):

$$ab(Ts) = 1.33\cdot(9.66 + Ts)^{2.85}$$

where Zf is the firn line altitude, dTs is average summer air temperature change, p is the change of annual precipitation, E is the gradient of specific mass balance at the elevation of the firn line.

Thus, if future changes of precipitation and average summer temperatures are known, it is possible to evaluate the change of the firn line altitude. The formula shows, that the higher the glaciations energy is, the more stable glaciation becomes towards climatic change.

The following equations are used to define the dependence of the glaciated area (Fg) on some characteristics of relief and firn line altitude.

They were also developed by Glazyrin (1985), and have subsequently been modified repeatedly. The latest version is:

$$Fg(Zf) = 5.55 \cdot (Z\max - Zf)^{0.98} \cdot Fb(Zf)^{0.51}$$

Here Fb(Zf) is the basin area that is located higher than the firn line, (Zmax – Zf) is the difference in altitude of the highest point in the basin and the firn line. A similar formula has been developed for the number of glaciers in a basin (Ng).

The total volume of glaciers in a basin (Vg) can be approximately calculated with the formula (Glazyrin 1991):

$$Vg = 0.05 \cdot Fg^2 / Ng$$

The glacier drain volume Wg can be estimated with the following simple formula:

$$Wg = ab(Zf) \cdot Fg$$

where ab(Zf) is the ablation at the average elevation of the firn line which can be calculated by Krenke-Khodakov's formula.

The following relations were revealed for the estimation of the share of glacial melt water in overall basin discharge (Wb):

$$Wg / Wb = 0.9 \cdot (Fg / Fb)^{0.7}$$

Indicated here takes place if a regularity of annual precipitation from the territory's altitude is prominent, and the following formula reflects concave dependence.

$$Wg / Wb = 0.9 \cdot (Fg / Fb)^{0.5}$$

Here Fb is the area of the river basin, while Fg denotes the glaciated area in it. All the data relating precipitation to elevation have been collected by Getker M. I. (Getker & Schetinnikov 1992).

As was already mentioned, glaciers have adapted to climatic changes for a long time. Therefore, the presented method only applies to those cases when the glaciation is completely adapted to new conditions, i.e. is in a stable state, which is an essential drawback of the method. However, it is possible to use it to make calculations of glacier modifications in a transitive regime.

Using the mentioned method, it is possible to estimate the sensitivity of glaciation to changes of climate. The calculations carried out for several river basins of Central Asia (Glazyrin et al. 2002) have shown that the glaciation is very sensitive even to slight climate changes. A 1 °C change in summer air temperature results in a lowering of the firn line altitude of approximately 120–140 m, a reduction of precipitation by 20 % causes the same effect.

The influence of the climate changes on the glaciated area of river basins is more complicated. Obviously, it depends both, on the distribution of precipitation with altitude, and on the topographic relief. Unfortunately, these factors vary from basin to basin affecting the various reactions of glaciers. For example, a 0.5 °C rise of temperature results in a reduction of the glaciated area by 8 % in the basins of the Sokh and Isfara, and by 30 % in the basins of the Magiyandarya, Kashkandarya and Oygaing rivers. A 1 °C temperature increase cuts the area of glaciation by half! It is appropriate to remind, that it is rather difficult to even detect or forecast such small changes in temperature. It was furthermore concluded, that a reduction of precipitation leads to similar results. That outcome is important to understanding the fast glacier response to almost imperceptible climatic modifications.

As was already mentioned, the prediction of glacier changes depends on climate change scenarios and projections, which are currently unreliable. Therefore, we estimated the probable reaction of glaciers to various combinations of changes in annual precipitation and summer temperature. Estimated changes in both glaciation and glacier melt water runoff for two river basins with the following characteristics are shown in Tables 5 and 6.

- The Zeravshan river: observation point called "the Fandarya mouth", basin area: 4650 km², glaciated area in 1980: 438 km², number of glaciers: 632, supporting meteorological station: Dekhauz.

- The Oygaing river: observation point called "The Mouth". The main quantity of the country's glaciers is concentrated here. Basin area: 1010 km², glaciated area in 1980: 59.5 km², number of glaciers: 128, Supporting meteorological station: Oygaing.

It becomes evident, that the glaciers in these two basins react differently to climate changes.

Table 5 Reaction of ice melt fraction in the Zaravshan river discharge on climate change

dTs, °C	Parameters	dX, %			
		–50	0	+50	+100
0	Zf	4.44	4.05	3.76	3.53
	Fg	182	438	666	868
	Ng	305	632	866	1039
	Wg/Wb	0.18	0.28	0.34	0.39
1.0	Zf	4.55	4.18	3.91	3.69
	Fg	128	338	544	733
	Ng	224	511	745	926
	Wg/Wb	0.15	0.24	0.31	0.36
2.0	Zf	4.66	4.31	4.05	3.84
	Fg	95.0	260	437	603
	Ng	175	415	631	804
	Wg/Wb	0.13	0.21	0.28	0.32
3.0	Zf	4.76	4.43	4.19	3.99
	Fg	60.5	186	331	484
	Ng	116	331	503	683
	Wg/Wb	0.10	0.18	0.24	0.29

Analogue calculations were made for basins of the Western Tien Shan and Pamir-Alai.

For example, for the most extreme case assuming a summer temperature increase of 3 °C and a precipitation decrease of 50 %, the glaciers in the Zeravshan's basin will remain fairly constant with the fraction of glacial melt water being about 10 % of the overall basin discharge. Under the same conditions the glaciers in the Oygaing basin will thaw completely.

It is necessary to point out that the reliability of the calculations is decreasing the more the assumed conditions are different from current ones due to the assumptions made in the development of the formulae. For instance, it was assumed that precipitation and air temperature in a basin change linearly.

The previous section shows, that there is a method to calculate the change of basin glacier characteristics to climate change. However, the results of the forecasting directly depend on the chosen scenario of climate change. It is difficult to choose the most reliable one. This problem has to be solved by climatologists, before a reliable forecast on the destiny of mountain ice in Central Asia can be made.

Table 6 Reaction of ice melt fraction in the Oygaing river discharge on climate change

dTs, °C	Parameters	dX, %			
		-50	0	+50	+100
0	Zf	4.11	3.73	3.45	3.23
	Fg	13.9	59.5	137	208
	Ng	62	128	226	285
	Wg/Wb	0.11	0.22	0.33	0.41
1.0	Zf	4.22	3.86	3.60	3.38
	Fg	6.8	34.5	95.3	159
	Ng	47	88	179	246
	Wg/Wb	0.07	0.17	0.28	0.36
2.0	Zf	4.33	3.99	3.74	3.54
	Fg	1.8	23.0	56.6	113
	Ng	28	75	123	200
	Wg/Wb	0.04	0.14	0.21	0.30
3.0	Zf	4.43	4.11	3.88	3.69
	Fg	–	13.5	32.8	71.5
	Ng	–	61	86	147
	Wg/Wb	0	0.10	0.16	0.24

River flow Monitoring

Agriculture is a significant part of the economic activity in Turkestan. It fully depends on the presence of water for irrigation and is, therefore, located preferably at the foot of the mountains or along large water arteries in the flatland, including the Amudariya, Syrdariya, and Zeravshan rivers. Therefore, a calculation of the available future renewable water resources of the territory is necessary before an economic plan for the development of the region can be devised.

Characteristics of the hydrological monitoring network

Systematic hydrometric monitoring of the rivers of Turkestan began at the end of 19th century on the main rivers of the Sirdariya river basin with some water level monitoring and the episodic measurement of discharge. The intensive development of a gauging station network was started in 1910 after the creation of the Hydrometric bureau in Turkestan headed by V.L. Glushkov, who has made invaluable contribution to the development of the hydrology in Central Asia. Streamflow monitoring was expanded rapidly: in 1916 at the time of implementation of the Hydrometric bureau, there were 33 posts measuring at 312 gauging stations, and in 1915, 114 posts measured at 1556 gauging stations. Subsequently, the monitoring network and method of monitoring was further developed and improved with some setbacks caused by economic and political circumstances.

In 1991, there were six working water balance station in the Central Asian region, four of them located in mountain areas, which are the source for irrigation water. Four posts included the monitoring of the evaporation from a water surface in evaporators with a surface area of 20 m², while about fifty posts were equipped with GGI-3000 evaporators for water surface evaporation monitoring and GGI-500 evaporators for land evaporation (Chub 2000). About 190 hydrological posts provided operative information to Tashkent used to forecast river discharge on a daily basis.

Table 7 shows the change in the number of hydrological stations and posts during the past 20 years. As can be seen, the hydrometric network has suffered particularly in Kyrgyzstan and Tajikistan, while it was possible to keep a significant part of it in Uzbekistan.

These numbers show, that beside the rapid decrease of meteorological and snow measuring networks, there was also a significant reduction of hydrometeorological information, which all led to the fact that large territories (some river basins, range slopes, highlands) are no longer fully covered by a (hydro-) meteorological and snow measuring network.

Table 7 Change of the hydrological monitoring network in Central Asia during recent years

State	Quantity of posts in years		
	1985	1996	2004
Uzbekistan	155	119	131
Kyrgyzstan	147	111	76
Tajikistan	139	85	81
Turkmenistan	38	23	32

A specific problem for hydrometric studies in Central Asia, especially long term studies, is the rapid increase of water collection from rivers. This problem particularly concerns low water flows which provide essential information on the local changes in runoff producing processes. Often, new developments are built upstream of long standing hydrological posts. Subsequently, water is diverted into other, small unmonitored river channels. This makes it necessary to look for ways of reconstructing natural water flows. This problem is also evident for large water arteries. For instance, the natural flow of the Syrdariya River is fully distorted even upstream of the Fergana valley. In order to obtain a multi-year runoff data set downstream of this valley, it is necessary to conduct some pretty complicated calculations on both actual river channel flows and flows of large diversions channels used to satisfy the irrigation needs. Multi-year river flow records of the Syrdariya and Amudariya rivers published by the U.N. were obtained using that particular method.

The worsening economic situation that caused a reduction of the monitoring network also caused problems in the provision of the hydrometric network with devices, equipment, spares, and materials. Existing fittings are almost worn out and new hydrometric flappers, windlasses, level loggers, and many other devices are currently not purchased.

The majority of the monitoring data is processed by hand. There has been a decrease of data exchange of many types of hydrological information between the hydrometeorological services of Central Asia.

This can lead to an informational vacuum, and prevent the development of new methods for forecasting river regimes and environmental pollution. There was also a significant brain-drain of professional experts from hydrometeorological networks and it seems impossible to stop that process in the near future due to financial difficulties. The previous points indicate the need to take urgent steps in order to improve the existing situation. To do that it is necessary to unite the efforts of all states of the region and to receive help from the international community (Chub 2000).

Particularities of the water flow regime, inter-annual variations, and long term flow normals

The runoff regime of rivers in Central Asia is well studied through the efforts of several generations of hydrologic scientists. A significant role in that process belongs to V. L. Shultz (1963), whose book "Rivers of Central Asia" describes the main aspects of accumulation, water balance, inter-annual and intra-annual water flows and other aspects of the regional river regime. That book has not lost its applicability up until today.

The second important publication of hydrologic knowledge was the multi-volume series of the fundamental books "Resources of surface water of USSR". A separate book was published for each large river basin and hydrological region. It is clear that the publication of this data is very beneficial nowadays, taking into consideration that the natural conditions of the mountain regions in particular during the most recent years practically did not change. Unfortunately, these books are hardly known by non-specialists. It should be mentioned, that the USSR Glacier Catalogue was created as a part of this huge work.

Three volumes are devoted to the region considered here (Resources of surface water of USSR 1969, 1971, 1973). The following briefly describes the main hydrological characteristics of Central Asia based on the above mentioned publicastions. When looking closely at a hydrographical map of Central Asia, the uneven distribution of surface water bodies including river systems becomes evident. Large areas occupying 70 % of the total territory possess only a small amount of the surface water. In distinction to flatland areas, mountain areas are characterized by bifurcated river system. Bifurcated river systems can also be seen at the foot of the mountains. However, the bifurcations have a different character in those areas, as they are mainly artificial irrigation channels, which do not concentrate flow in the main rivers, but rather divert it away from the river network and disseminate it to neighbouring areas.

The different directions of water flow processes in mountains and flatlands caused V. L. Shultz to outline an area of flow concentration corresponding with the mountain regions of Central Asia, and an area of flow diffusion corresponding to the part of the flatlands which evaporate surface water back to the atmosphere.

The continental location of Central Asia and its exposure to northern climate conditions result in a strongly continental, dry climate, with dry, cloudless, and hot summers and relatively humid winters, sometimes accompanied by strong frosts. Therefore, the biggest part of Central Asia is covered by continental deserts. The numerous mountain ridges have a huge influence on the environment and, therefore, flow processes as they receive the bulk of the precipitation. The large variability of the land surface leads to the fact, that Central Asia is a region of big contracts where dry areas are located closely to humid ones, and sometimes snow fields and glaciers are removed from sultry deserts by a distance not exceeding 100 km. Calculations of O. A. Drozdov (1954) show that precipitation in Central Asia relies almost exclusively on external moisture sources. Precipitation originating from locally evaporated surface water makes up only a small fraction of overall precipitation. It is furthermore interesting to point out that only about 18 % of the available precipitable water actually reaches the territory. Therefore, even at the high mountain ranges only a small amount of the atmospheric moisture being transported above Central Asia is actually raining down on it. An even lower amount is actually running off from the mountain areas into flatlands. This shows that mountains serve as an important climate and hydrological factor, and more importantly, as condensers of atmospheric moisture.

The intra-annual distribution of precipitation can also be explained by the influence of the mountains. The flatlands and the western peripheries of the mountains receive maximum precipitation amounts in March and April, while mountainous areas exhibit a mid-summer maximum. Annual precipitation generally increases with elevation in most of Central Asia, except for the northern parts (Resources of surface water of USSR 1971). The steep slopes in the mountains cause a quick concentration of (mostly melt-) water flow into the river systems. Large amounts of precipitation, relatively low evaporation rates, and steep slopes define the hydrological regime of the headwater streams of the region. Having their source in the high mountain areas, the rivers are mainly fed by the melt of seasonal snow covers and glaciers, and plentiful subsurface water, which again stems mainly from melt water. Due to the presence of a vertical temperature gradient, snow and ice melt does not happen simultaneously in the whole catchment area of a river, but rather moves up gradually throughout the spring and summer. This process combined with the presence of large snowfields and glaciers leads to a freshet that is extended over a long time and usually does not produce high flow peaks.

The melt generally begins very late in the high elevation, permafrost zone containing seasonal snow covers and glaciers. Therefore, rivers that are mainly fed by the melt water of high mountain glaciers and snow covers often have their annual peak water flows in July. Rivers originating at mid-elevations and being fed mainly by the melt water of seasonal snow covers, can be distinguished by the early passage of the spring freshet peak (March – May) and rather big fluctuations of annual flow due to the fact that the annual flow volume fully depends on the amount of snow deposited since the previous fall. Finally, for rivers originating from low elevations, where rain is the most important source, large flows follow significant precipitation events in short order. Mud flows are formed particularly by these kinds of rivers.

V. L. Shulzt has developed a logical classification of Central Asian rivers describing river regimes based on the proportion of summer (July – August) ($W_{VII\text{-}IX}$) to spring (March to June9) $W_{III\text{-}VI}$ flow (Table 8). This classification proved to be very informative for the research of river regimes in the region.

The following describes some general characteristics of mountain rivers in Central Asia, based on the "Resources of surface water of USSR" books.

- Annual runoff efficiencies are continuously increasing with altitude from 3 – 4 $l \cdot s^{-1} \cdot m^{-2}$ in low lying areas to 40 – 50 $l \cdot s^{-1} \cdot m^{-2}$ in the mountains. Only at the highest elevations above the firn edge of glaciers they can decrease again.
- At similar altitudes, annual flow volumes are higher on the wind exposed western slopes while inside-mountain areas show decreased volumes.
- The coefficient of variation of annual flow is decreasing with an increasing average altitude of the headwaters. It also decreases with an increase of the relative ice coverage in the basin. This is due to the fact that glaciers regulate annual flows, i.e. in years with small amounts of precipitations they compensate the lack of snow melt water by a strengthened melting; in years with large amounts of precipitation, their balance is positive and they accumulate water as firn and ice, preventing it from running off that year.
- Flow distribution within the year depends on the type of river source (Table 8). As the altitude of water collection grows the maximum of the freshet is shifted towards summer.
- The larger the range of elevations in the basin, under otherwise equal circumstances, the more the freshet is extended, and the lower the annual flow maximum compared to annual average flows. Consequently, the duration of low river flows decreases with altitude.

These are the main characteristics of the headwater basins in the mountains of Central Asia. However, a special role belongs to melt waters and they should, therefore, be discussed separately. A significant contribution to its study was made by O. P. Sheglova (1960) in addition to V. L. Shultz.

Table 8 Classification of Central Asian rivers

Flow Sources	Criteria serving for the identification of rivers to one or another type of accumulation		
	$\delta = \frac{W_{VII-IX}}{W_{III-VI}}$	$W_{VII\text{-}IX}$ in percent of annual flow	Months with maximum annual flow
1. Glacier and snow	≥ 1.00	≥ 38	VII – VIII
2. Snow and glacier	0.27 – 0.99	17 – 40	V – VI
3. Snow	0.18 – 0.27	12 – 16	IV – V
4. Snow and rain	0.00 – 0.26	0 – 13	III – V

The role of melt water in the river flows of Central Asia

As previously mentioned, melt waters play a dominating role in the accumulation of mountain rivers. The classifications listed in table 8 further illustrate this. This is the case even for most high mountain rivers; if the hydrometric post is not located right at the tongue of the glacier itself, the contribution of snow melt water generally exceeds the other accumulation sources.

There is some discussion amongst glaciologists about the definition of river glacier accumulation. V. L. Shultz (1963) understood it as only ice melting. i.e. only the melt of glacier tongues. Many hydrologists, including O. P. Sheglova and many glaciologists include the melt water from seasonal snow covers deposited on the entire glacier area. Formulae to calculate the glacier runoff based on the fraction of the basin covered by glaciers are based on ice runoff calculations using this definition. Obviously the composition of the river flow depends on the location of the hydrometric station in the basin. For instance, if a post is located close to a glacier then the role of glacier water will be a dominating one; if the post is located on the same river at the exit of the river from the mountains, then its fraction will be significantly less.

General characteristics in flow components in the area are listed below:

- The higher the basin is located, the larger the contribution of snow and ice melt water to river flow.
- The closer the maximum of precipitation is to summer the higher the contribution of liquid precipitation and the lower the fraction of melt water.

In conclusion of this part, we would like to show an assessment of the contribution of ice and snow melt water to the flow of the main rivers of Central Asia – Syrdaria (Bekabad post) and Amudariya (Kerki post), based on data calculation, contained in the books (Resources of surface water of USSR 1969, 1971) (Table 9).

The role of glacier and ice components in river flow in conditions of global warming and degradation of permafrost

First of all, it is necessary to mention that the warming itself will not lead to significant changes in the annual flows of mountain rivers because

Table 9 Fraction of glacial melt water in the flow of the main rivers of Central Asia

River	A	B	C	D
Syrdariya	142 000	830	1.8	7
Amudariya	309 000	2070	~2.6	9

A – contributing area in km²;
B – long term average flow in m³/s;
C – fraction of basin area, covered by glaciers in %;
D – average fraction of glacier melt water in annual flow in %

evaporation depending on air temperature is not significant. Apparently, even the total disappearance of glaciers does not influence the water resources, since they mainly depend on the annual amount of precipitation. Figure 14 confirms this, showing that up to 2000 there was no significant negative trend of annual flow volume of the Syrdariya and Amudariya rivers (data of U.N. Ivanov), although warming in these years was not significant. At the same time, the reduction of snow and ice resources should lead to significant redistribution of runoff within the year. However, from the point of view of the economy, this is not that important because natural flows of big and small rivers are regulated by numerous hydrotechnical constructions.

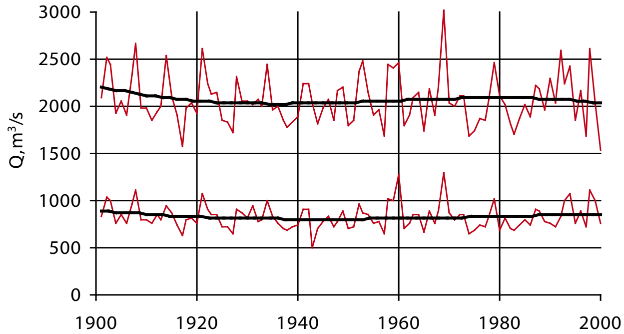

Figure 14 *Long term annual flows of the Syrdariya (bottom diagram) and Amudarya (upper diagram)*

Prognostic evaluations of possible drain change

As previously mentioned, all predictions of future river flows must be based on long term climate projections. Taking into consideration the low reliability of these, it is not feasible to present calculation results of future river flows for the numerous scenarios of future climate change. Instead we will discuss some likely general trends:

- Annual amounts of atmospheric precipitation play the biggest role in flow changes. However, all scenarios of climate change project precipitation to be constant or slightly increasing. Therefore, no significant changes of annual flow volumes are expected.
- An increase of air temperature can slightly change basin outflows, firstly, due to some decrease of evaporation, and secondly, due to the decrease of solid precipitation. This will decrease snow deposits and resulting melt water flows and, consequently, overall flow volumes since the runoff coefficient of melt water is slightly higher than that of rain water.
- If the basin has significant ice coverage, then the increase of air temperature will slightly increase the runoff in the short term due to additional melt water input from the increased melt of glaciers. After the glaciers adapt to the new climate conditions, the basin runoff will again depend, mainly, on yearly amounts of precipitation.
- The inter-annual variability in flow will increase due to the declining role of flow regulating glaciers.
- Temperature increases should be reflected in the flow regimes of Central Asian rivers with the freshet drifting to the spring and maximum flows of melt water slightly increasing due to a faster spring melt. Existing, numerous, evaluations of river flow changes as a result of climate change reflect particularly that process.

Summary and Conclusions

This paper briefly considers the history of meteorological, hydrological, and glacier monitoring in the mountain regions of Central Asia, and summarizes the applied methods of measuring, as well as the degradation of monitoring system after the failure of the USSR. Long term changes of the main climate characteristics (air and precipitation temperature) are illustrated, as were changes in snow covers and glaciers based on previously unpublished information, which we had access to. River flow characteristics of Turkestan streams are described briefly, and a long term study by several generations of professional experts is presented.

The study explores some methods, which could be utilized in the long-term forecasting of hydrologic and glacier changes as a result of possible further climate change. It is necessary to point out again that such projections are based on multiple climate scenarios, whose reliability is currently insufficient for any type of reliable prognosis of the future climate of the region.

Acknowledgements

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Monitoring of water, snow and glacial resources of Kyrgyzstan

V. Kuzmichenok

This paper presents the past and present state of the monitoring network of water, snow, and glacial resources in the Republic of Kyrgyzstan. The study furthermore assesses the current (as of 2005) situation of these resources.

General Background

The Kyrgyz Republic is situated in Central Asia within the latitudes of 39 °N – 43 °N and longitudes of 69 °E – 80 °E. Elevations in the country range from 500 to 7400 m a.s.l. Its territory covers most parts of the Pamir-Alay and the western half of the Tien-Shan, both of which are essential regions for the runoff formation of rivers in Central Asia. Based on previously obtained digital relief models and precipitation conditions of Kyrgyzstan (Kuzmichenok 2003), the following average reference values were calculated:

altitude	2684 m
slope angle	10.1°
alignment indicator	0.926
mean curvature	0.00068 km^{-1}
average annual air temperature	–0.09 °C
annual total of precipitation	118.30 km^3 (614.2 mm)
potential evaporation	882.3 mm
actual evapotranspiration	70.82 km^3 (367.69 mm)
annual unit discharge	8.26 l/skm^2
total annual runoff	47.48 km^3 (246,51 mm)
moistening	0.696

The territory of Kyrgyzstan is covered by 8 major hydrological basins shown in figure 1.

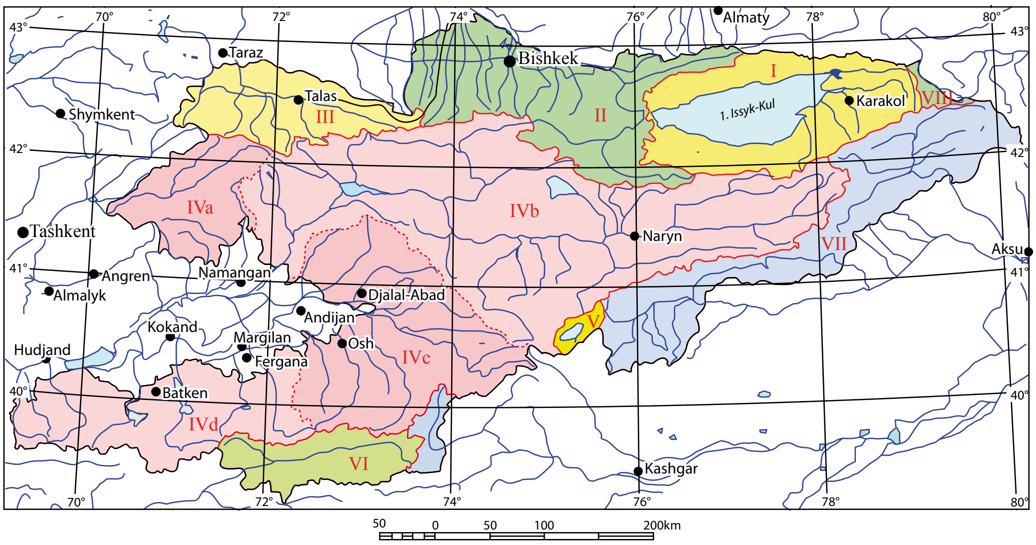

***Figure 1** Major hydrological basins of Kyrgyzstan*

The symbols for the basins specified in figure 1 and in the subsequent text are as follows:

- I Issyk-Kul Lake;
- II Chu-river;
- III Talas-river;
- IV Syrdarya river;
- IVa rivers of the northern borders of the Fergana valley (Syrdarya river);
- IVb Naryn river (Syrdarya river);
- IVc Karadarya river (Syrdarya river);
- IVd rivers of the southern borders of the Fergana valley (Syrdarya river);
- V Chatyr-Kul Lake;
- VI Amudarya river;
- VII Tarim river;
- VIII Balkhash Lake.

The major parameters of the hydrological basins within the territory of Kyrgyzstan are listed in table 1. The following symbols have been adopted:

- S area;
- H average elevation;
- U mean angle of slope;
- C mean curvature;
- Po average alignment indicator (Kuzmichenok 1979);
- T average annual air temperature;
- P annual sum of precipitation;
- E* potential evaporation;
- E actual evaporation;
- EF transpiration of forests;
- F runoff;
- M discharge per area (l/skm^2);
- D moistening.

Table 1 Some parameters of the major hydrological basins of Kyrgyzstan

Parameter	Hydrological Basins							
	I	II	III	IV	V	VI	VII	VIII
S (thous.km²)	15,38	22,27	10,77	110,79	0,92	7,70	24,08	0,69
H (m)	2606,3	2166,4	2178,8	2541,8	3703,6	3559,7	3762,4	3138,7
U (degrees)	9,41	8,59	9,64	10,38	5,06	10,55	10,60	8,83
C (km^{-1})	0,00126	–0,00002	0,00017	–0,00092	0,00882	–0,00010	–0,00228	–0,00352
Po	0,9243	0,9179	0,9184	0,9284	0,9497	0,9306	0,9244	0,9159
T (°C)	0,76	2,45	1,87	0,92	–7,64	–2,76	–7,27	–4,17
P (mm)	585	552	578	634	415	573	634	794
P (km^3)	8,99	12,29	6,22	70,19	0,38	4,42	15,26	0,55
E* (mm)	931	976	915	943	458	853	504	603
E (mm)	332	364	359	369	257	364	282	374
E (km^3)	5,10	8,10	3,86	40,87	0,24	2,81	6,79	0,26
E_F (km^3)	0,54	0,17	0,02	2,02	0,00	0,01	0,04	0,00
F (mm)	218	181	217	246	158	207	350	420
F (km^3)	3,35	4,03	2,33	27,31	0,14	1,60	8,43	0,29
M ($l./s.km^2$)	6,91	5,73	6,86	7,81	5,00	6,57	11,09	13,31
D	0,628	0,566	0,631	0,672	0,907	0,672	1,258	1,316

It should be noted, that to develop digital models of potential and actual evaporation, we have developed the following regional (for the territory of Kyrgyzstan and adjacent territory) statistical dependencies (Kuzmichenok 2003):

$$E^{*}=[0.00005581(27.24+T)^{3.0889}]\cdot[0.7956+0.1155\cdot H\cdot e^{0.3279\cdot H}]\cdot[0.3622+0.00483\cdot P^{-0.9043}] \qquad (1)$$

with E* being annual potential evaporation (m); T mean annual air temperature (°C); H altitude (km a.s.l.); and P the total of precipitations (m). And:

$$E=\frac{(P\vee E^{*})\cdot[0.6265\cdot(2.6578-ch^{1,0625}U)+0.2264\cdot thC-(0\vee 0.7955)]}{\left\{1+\frac{0.9016\cdot P^{0,9409}}{[E^{*}+0.0884\cdot(P_{O}-0.94)]^{0.5561}}\right\}^{0.7307}} \qquad (2)$$

with E being surface evaporation (m); U the angle of slope (°); C mean surface curvature (km^{-1}); P_O the surface alignment indicator; ∨ a Boolean "or" operation (disjunction); ch hyperbolic sine; th hyperbolic tangent; (P∨E*) minor value; and (0∨0.7955) a significant effect, if the mesh point covers a wooded area.

Climate Monitoring

It is well known that the first meteorological stations were established in the territory of modern day Kyrgyzstan at the end of 19th century. Systematic and uniform meteorological measurements were initiated in the third quarter of the 20th century. The network of meteorological stations and hydrological posts reached its maximum extent in 1985, when 79 meteorological stations (including specialized ones) and 149 hydrological posts were operating at the same time. Today, the number of meteorological observation stations has seriously decreased with only 40 meteorological stations (including 6 automated ones) and 76 hydrological posts operating nowadays (MCHS 2003).

To study the variations of mean air temperatures on the territory of Kyrgyzstan over time, the following publications were used: Bokonbayev et al. (2003) and MCHS (2003), which most comprehensively summarize the results of measurements made until 2000. Additionally, this study includes further measurements made until 2005, inclusive, and presented to the author in a different project framework. Just like in MCHS (2003), we shall use the following separate regions for the assessment of climate variables: NNEK – North, North-East Kyrgyzstan; SWK – South-West Kyrgyzstan; IKB – Issyk-Kul Basin; ITS – Inner Tien-Shan.
The results of calculations of linear trends of mean annual temperatures as well as January and July air temperatures for the period covered by MCHS (2003) and for the last 15 years (1991 – 2005) are listed in table 2.

It becomes evident from table 2, that the trends of mean annual air temperatures increase both, in individual areas and in Kyrgyzstan as a whole, have intensified significantly for the last 15 years, mainly due to an increase of winter temperatures. Just like for the previous period, linear trends of air temperatures for the last 15 years are minimal for the Issyk-Kul basin, which can be attributed to the mitigating impact of the large lake. For the last 15 years there has also been a clear trend of decreasing summer air temperatures. It should be noted, that linear trends of time series, as a rule, are dependent on the length of the used time series. Therefore, we should be rather careful when comparing the trends for time series of different lengths. Thus, linear trends of air temperatures for "sliding" 15-year periods (1926 – 1940, 1927 – 1941, […], 1991 – 2005) were calculated for 5 meteorological stations within Kyrgyzstan. The results are presented in figure 2.
It should be noted that the presented graphs do not confirm the assumption that absolute values of trends of mean air temperatures in the last 15-year period (1991 – 2005) are considerably different from previous time periods, although it also becomes obvious, that lately, increasingly positive trends of mean annual and January air temperatures have been observed. The obtained time series were also statistically checked for "significance" of trends using the F-criterion (Fisher-Snedekor distribution) of ratio of dispersions of deviations from the mean value and deviations from the linear trend equation. In most cases an "insignificant" relation of dispersions was identified (admissible at the 10 % significance level and with the number of degrees of freedom being 13 and 14, with the criterion value being 2,55 (Smirnov & Belugin 1969).

Table 2 Linear trends of mean air temperatures in Kyrgyzstan (°C/year)

Area	Meteorological station	From late 20s			Over 1991 – 2005		
		Year	January	July	Year	January	July
NNEK	Bishkek	0.020	0.022	0.010	0.089	0.205	–0.053
	Baitik	0.008	0.017	0.005	0.054	0.124	–0.048
SWK	Pacha-Ata	0.006	0.029	–0.001	0.055	0.239	0.007
	Sary-Tash	0.024	0.037	0.017	0.049	0.119	–0.016
IKB	Balykchi	0.023	0.021	0.029	0.030	0.054	–0.038
	Cholpon-Ata	0.024	0.036	0.015	0.043	0.063	–0.016
ITS	Naryn	0.012	0.052	0.005	0.061	0.187	–0.031
	Suusamyr	0.012	0.005	0.019	0.089	0.290	–0.075
	Tien-Shan	0.012	0.011	0.012	0.160	0.360	0.028
Kyrgyzstan (entire territory)		0.016	0.026	0.012	0.070	0.182	–0.027

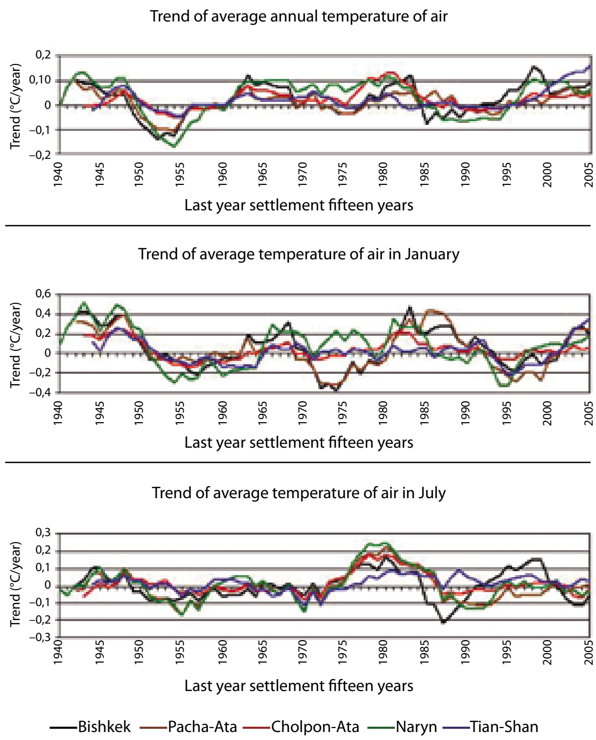

Figure 2 *Linear trends of air temperatures in "sliding" 15-year periods*

The graphs in figure 2 also show a rather good consistency of the variations of linear trends of mean air temperatures over time at different meteorological stations. As a result, mean values of the 10 twin correlation coefficients for these five meteorological stations were 0.63 for mean annual temperatures, 0.66 for January temperatures, and 0.64 for July air temperatures. This suggests, without going into a more detailed statistical study, that the total data supplied by several meteorological stations rather evenly distributed across the territory, can adequately characterize the variations of mean air temperatures throughout all of Kyrgyzstan.

Precipitation amounts in inland Kyrgyzstan have been measured both at meteorological stations and hydrological posts. Measurements made through accumulative precipitation gages, as a rule, are rather discontinuous (rarely more than eight years), have more gaps and, on the whole, are less reliable. When establishing the abovementioned digital model of annual total precipitation amounts, the author used initial data from 304 meteorological stations and hydrological posts (including some located in neighbouring countries), including 23 accumulative precipitation gages, and 103 interpolation points, where the annual precipitation total was calculated based on air temperatures, glacial information, and regional statistical dependencies obtained previously (Kuzmichenok 2003) and described below:

$$P_f = 744.1 + 99.5T_{sf} \quad (3)$$

with P_f being an annual total of precipitations at the equilibrium line (mm), Tsf being the mean summer air temperature at the equilibrium line.

Listed below (Table 3 and Figure 3) are linear trends of total precipitation calculated similarly to the analysis of air temperature variations. The graphs shown in figure 3, do not exhibit a good correlation of variations of the total of precipitations at different meteorological stations. Consequently, mean values of the 10 twin correlation coefficients for these 5 meteorological stations were 0.25 for annual; 0.40 for January and 0.47 July totals of precipitation.

Table 3 Linear trends of total precipitation in Kyrgyzstan (mm/year)

Oblast	Meteorological station	From late 20s			Over 1991 - 2005		
		Year	January	July	Year	January	July
NNEK	Bishkek	0,93	0,13	–0,11	10,26	0,96	1,08
	Baitik	0,31	0,12	0,04	–20,67	0,15	–11,65
SWK	Pacha-Ata	2,39	0,16	0,36	–3,96	0,69	–2,65
	Sary-Tash	0,61	0,10	–0,05	2,39	–0,73	1,26
IKB	Balykchi	0,05	0,00	–0,01	1,18	0,49	–0,66
	Cholpon-Ata	0,59	0,00	0,01	–0,26	0,32	1,13
ITS	Naryn	0,11	–0,48	–0,01	1,52	0,25	–0,99
	Suusamyr	–1,67	–0,06	–0,14	7,38	0,25	1,49
	Tien-Shan	–1,26	–0,02	–0,44	23,02	0,31	3,39
Kyrgyzstan on the whole		0,23	–0,01	–0,04	2,32	0,30	–0,84

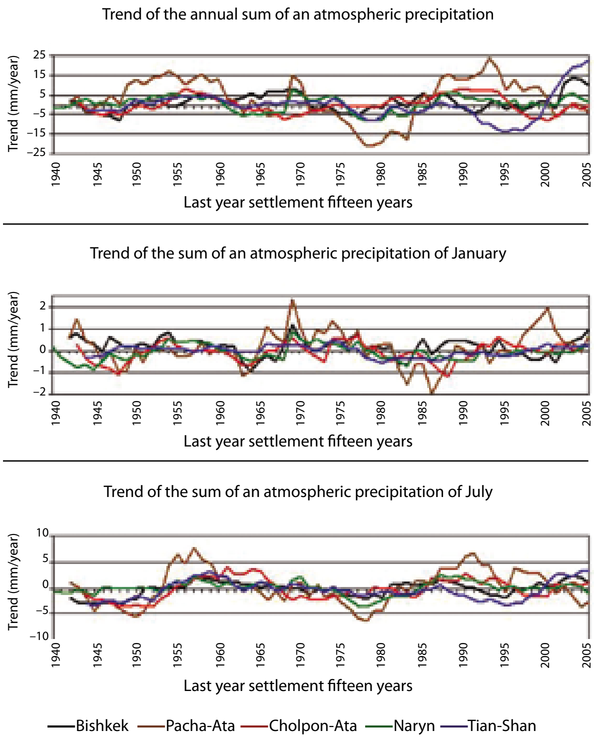

Figure 3 *Linear trends of the total precipitation within "sliding" 15-year periods*

As for the total precipitation in inland Kyrgyzstan, it can be stated, though with less confidence, that positive trends of their annual totals have slightly increased recently. As was the case for air temperatures, a more detailed statistical study was not performed.

However, it can tentatively concluded, that the available meteorological stations less adequately (compared to air temperature) characterize the variations in total precipitation across all of Kyrgyzstan.

As a summary, we believe it is worthwhile to mention another of the author's studies carried out under a different project's framework, which addressed the variations of the water level and other properties of the Issyk-Kul Lake. This study was based on the abovementioned digital relief models and precipitation conditions (Kuzmichenok 2003), as well as on the results of the mathematical-cartographic modeling of mean long-term values of the moisture-circulation components of the Issyk-Kul basin (Kuzmichenok 2006) and assessments made through a recording depth meter within the Issyk-Kul Lake (Kuzmichenok 2005). The study modeled possible variations of lake parameters for different scenarios of climate changes (MCHS 2003). Furthermore, it selected a scenario of linear trends of mean air temperature and annual precipitation total for a 100 year period (1968–2067). The selection was based on a best fit (minimization of the root-sum-square uncertainty) simulation of water levels in the Issyk-Kul Lake compared to actual measurements over the period 1969–2003. The chosen scenario included a linear 2.4 °C increase of mean annual air temperature in the Issyk-Kul basin over 100 years and a 14 % linear increase of mean annual total precipitation over the same time period. Overall, the obtained climate conditions do not contradict the data listed in Tables 2 and 3 for the Issyk-Kul basin. The results of the modeling using the described scenario of climate change are illustrated in figure 4. The lower rate of water level decline in the Issyk-Kul Lake in the middle of the considered 100-year period can be attributed to accelerated "drawdown" of basin glaciers, also considered in the modeling process.

Snow Cover Monitoring

Snow cover plays an essential role for the territory of Kyrgyzstan as an important factor impacting climate and affecting almost all aspects of human life and activities. According to preliminary calculations, of the long-term average annual volume of precipitation

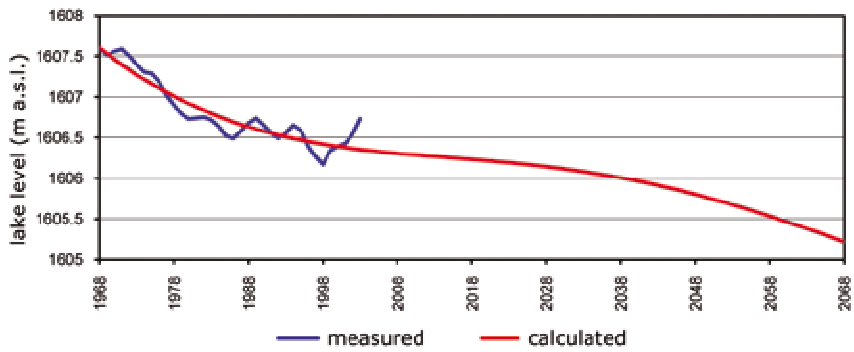

Figure 4
Measured and calculated water-level of Lake Issyk-Kul for a linear climate change scenario (dT = 2.4 °C and mP = *1.14 over 100 years)*

of 118.30 km³ covering inland Kyrgyzstan, 42.94 km³ falls as liquid precipitation, while 54.93 km³ consists of solid precipitation and 20.43 km³ is mixed.

The properties of the snow cover for the mountainous Kyrgyzstan have an even greater spatial (especially based on elevation) and temporal variability than total precipitation. Overall, the observations of snow cover variations for the territory of Kyrgyzstan are rather heterogeneous and have abruptly dropped in the early 1990s.

During the period of highest development, there were 4 ways to measure snow cover properties:

1. Measurements through surveyor's poles at meteorological stations and hydrological posts.
2. Route snow surveys around meteorological stations and hydrological posts (at fixed routes) and snow surveys in the upper reaches of river basins (at stationary snow points).
3. Helicopter measurements of snow cover thickness through distant surveyor's poles.
4. Measurements of snow cover thickness at avalanche catchments through distant surveyor's poles.

Measurements carried out using method 1 were published on a regular basis, while results from the other observations, as a rule, are retained in the Kyrgyzhydromet archives only. Results of snow cover property measurements, acceptable for statistical processing, have been published in "Nauchno-prikladnoj spravochnik po klimatu" (1989) for 32 meteorological stations only and in "Spravochnik po klimatu SSSR" (1969) for 92 hydrological posts. Measurements performed with methods 2 through 4 were much more numerous. E.g., in the winter 1984/1985 (Materialy nablyudenij nad snezhnym pokrovom i osadkami v gorakh 1987) the following snow-measuring stations and distant surveyor's poles were involved in measurements: 94 inland (route) snow-measuring stations in 7 river basins: 271 air distant surveyor's poles in 18 river basins; 319 distant surveyor's poles at 95 avalanche catchments in 13 river basins. These figures likely represent close to the maximum number of observations per winter for the entire period of observations. However, by now observations carried out with these methods have ceased entirely.

To study average long-term values of the snow cover thickness within a period of 10–15 years, we assume that we may use an even larger number of measurements. E.g., in the process of studying the snow load in the territory of the Tien-Shan, O.Podrezov (Podrezov 2000) used observations of 393 snow-measuring stations in 16 river basins, 564 air distant surveyor's poles in 29 river basins, and 198 route snow survey at meteorological stations and hydrological posts. However, most of these data is likely to be of little use for studies of snow cover dynamics in Kyrgyzstan.

Summaries of precipitation and snow cover in the territory of Kyrgyzstan (see, e.g., Dikih 1978; Ponomarenko 1976) do not include information about the variation of snow cover properties over time. The author is also not aware of any summaries of such studies that would have been done recently. There are publications covering individual territories and studies of temporal variations of some snow cover properties in regions bordering Kyrgyzstan. E.g., a study by Semakova et al. (2005) reported a more than 5 % reduction of snow cover in the Tashkent district at the end of March for 16 years (1989–2004). Semakova, (2004) found a slight reduction of maximum snow thickness at the Ducant meteorological station (Western Tien-Shan) for 33 years (1965–1997) and an overall reduction of maximum snow volume in the Ducant river basin. Such conclusions are well supported by the observed increased air temperatures in the region combined with observed insignificant variations of total precipitation. However, the authors would argue that studies about the variations of snow cover properties over time in the entire territory of Kyrgyzstan should be based upon more extended raw data. It would also be preferable to perform such studies not only at the point (observation stations) scale, but distributed throughout the entire territory using digital models of relevant properties.

Glacier Monitoring

Glaciers cover about 4 % of the total territory of Kyrgyzstan. The following are rather uniform, complete, and comprehensive sources of information on glaciers of Kyrgyzstan: Catalogue of USSR glaciers and the Modern Glaciation map of 1:500000. The glaciers of Kyrgyzstan have been described in 24 Sections and 1 Annex to the Catalogue, published over the period from 1968–1982. In the process of compilation, the authors of the Catalogue used air photographs and topographical maps starting from 1943. Therefore, we can assume that glacial information, on average, refers to the 1960s.

The Modern Glaciation map has been compiled from satellite images taken from 1977–80, but, unlike the Catalogue, it contains almost no numerical data on glaciers. According to the Catalogue of USSR glaciers and our estimates (Kuzmichenok 1993), there are about 8,208 glaciers in Kyrgyzstan with a total area of 8,076.9 km² and volume of 494.7 km³. According to the Modern Glaciation map, the area of glaciers can be estimated at 7,400 km². The difference can be attributed to both, time difference and inevitable errors of both sources of data. Information provided in the Catalogue has been complemented in the previously-established database (Kuzmichenok 1993) with geographical data of the centers of every glacier. It should be noted, that all estimates include the upper reaches of the North Inylchek Glacier which, from a geographical viewpoint, has been rather absurdly cut off by the state border with Kazakhstan.

However, if we want to be formally correct, we would have to subtract 16 from the number of glaciers, 90 km² from the area and 5.5 km³ from the volume. Please also note that in all the estimates we used the Kyrgyz borders inherited from the USSR without consideration of recent agreements on the state border. These new borders have not been specified in published state geographical maps to the best of the author's knowledge.

Table 4 Summary of the glaciers of Kyrgyzstan according to Catalogue of glaciers of USSR

	K	S	V	AAR	Lm	Sm	Tm	ELA
All glaciers	8208	8076,9	494,7	0,54	1,58	0,98	61,3	4203
Glaciers of different morphological types								
Hanging	2347	290,0	9,1	0,53	0,68	0,12	31,3	4098
Hanging corrie	866	332,3	12,3	0,53	0,94	0,38	36,9	4070
Corrie	2118	875,6	32,2	0,50	0,96	0,41	36,8	4075
Corrie valley	763	756,4	31,8	0,51	1,71	0,99	42,1	4061
Valley	1768	5434,6	390,8	0,55	3,07	3,07	71,9	4232
Slope	124	179,7	9,4	0,57	1,56	1,45	52,6	4429
Flat-topped	208	205,2	9,0	0,75	1,33	0,99	43,9	4280
Couloir	14	3,1	0,1	0,44	0,94	0,22	34,0	4057
Glaciers of different areas (sq.km.)								
Less than 0,11	2314	155,2	4,1		0,47	0,07	26,3	4045
0,11 - 0,30	1855	447,8	15,1	0,49	0,77	0,24	33,6	4044
0,31 - 1,00	2368	1445,2	54,0	0,50	1,35	0,61	37,3	4087
1,01 - 3,00	1146	2005,7	89,4	0,52	2,49	1,75	44,6	4119
3,01 - 10,00	451	2272,1	137,1	0,57	4,43	5,04	60,3	4172
10,01 - 30,00	62	961,5	96,8	0,62	8,56	15,51	100,7	4302
30,01 - 100,00	11	565,8	61,2	0,49	18,48	51,44	108,1	4548
Over 100,00	1	223,6	37,0	0,45	60,50	223,60	165,4	4500
Glaciers of different exposition compass points								
N	2855	2888,1	166,7	0,54	1,58	1,01	57,7	4126
NE	1551	1223,5	70,4	0,53	1,42	0,79	57,5	4290
E	517	452,5	25,2	0,55	1,57	0,88	55,7	4221
SE	452	473,8	23,5	0,55	1,76	1,05	49,6	4279
S	489	542,4	31,0	0,60	1,69	1,11	57,1	4266
SW	339	263,4	12,6	0,56	1,54	0,78	47,9	4227
W	471	512,9	38,2	0,44	1,70	1,09	74,6	4268
NW	1534	1720,3	127,1	0,55	1,60	1,12	73,9	4200

The common information on Kyrgyz glaciers (obtained from the Catalogue of USSR glaciers) is listed in table 4. All the information, except for volume estimates, has been obtained through direct calculations based on the Catalogue data. Glacial volumes which, as a rule, are not estimated in the Catalogue, have been calculated individually for each glacier based on statistical relations and based on their parameters known from the Catalogue. These statistical relations were based on rather reliable initial data on the volumes of eight Kyrgyz glaciers and on the results of a topographical survey of glacial beds with a radiolocation method (Kuzmichenok 1996b).

The following symbols have been adopted in table 4: K – number of glaciers; S – total glacial area (km²); V – estimated total glacial volume (km³); AAR – share of accumulation area within the total area; Lm – average glacial length (km); Sm – average glacial area (km²); Tm – average estimated glacial thickness (m); ELA – elevation of equilibrium line.

The author also calculated the distribution of glacial area in Kyrgyzstan at 100-meter elevation intervals based on equations from Kuzmichenok (1996a). The obtained distribution indicates that the maximum area of glacial surfaces in Kyrgyzstan is concentrated within the elevation interval of 4100–4200 m. Overall, about 45 % of all glaciers of the ex-Soviet Central Asian Republics and about 47 % of their total areas are located in the territory of Kyrgyzstan (Tien-Shan and Pamirs-Alay).

There were detailed glaciological observations (measurements of mass balance for at least 5 subsequent years) carried out at 4 glaciers in the territory of Kyrgyzstan. The locations are specified in figure 5. At the Golubina Glacier, observations were carried out by the Kyrgyz Unit of the hydro-meteorological service of the USSR, at the Kara-Batkak Glacier by the Academy of Sciences of the Kyrgyz SSR, at the Abramov Glacier by the Central Asian Scientific-Research Hydrometeorological Institute, and at the Sary-Top Glacier by the Institute of Geography of the Academy of Sciences of the USSR (5 years). Information on the mass balance of these glaciers was published many times. Summaries of such information can be found, for example, in Glazyrin et al. (1993) and Dyurgerov et al. (1992). Unfortunately, these observations were terminated in the early 1990s.

The variations of Kyrgyz glaciers over time were studied many times with a different degree of detail and through different methods. It is likely that the first semi-instrumental topographic glacial survey in Tien-Shan was a survey of the Petrov glacier terminus in 1869 done by an expedition headed by A.Kaulbars (Kaulbars 1875). It is furthermore likely, that the first activities related to the study of glacial variations in the territory of Kyrgyzstan, based on instrumental methods, were launched in 1932–1933 by the Naryn-Khantengri expedition (Vorobiev 1935). In the following years a great number of activities related to the assessment of the location of the lower termini of individual glaciers in Kyrgyzstan (see, e.g. Bakov 1982; Bondarev & Zabirov 1964; Dikih and Kuzmichenok 1981; Kanaev et al. 1974; Koshoev 1986; Kuzmichenok 1986), were initiated. We should also mention the large-scale photographic theodolite surveys of the termini of some Tien-Shan glaciers during the IGY (Zabirov & Knizhnikov 1962). It is likely that the first paper studying a single glaciation center (covering both variations of glacial borders and variations of their surface elevation), was a study mapping the glacial variations along the Ak-Shyirak ridge from 1943 to 1977 done in the 1980s by the Kyrgyz air-geodesic enterprise of MMGM USSR (Kuzmichenok 1989, 1990a, 1990b, 1991). The study was based on the strict stereophotogrammetrical processing of air photographs taken at different times. The map (Kuzmichenok 1990b) was rather highly appraised by specialists (Bondarev & Kravtsova 1993), though lately it has been criticized (Osipova et al. 2005). It is also prudent to mention a rather thorough and laborious paper of Schetinnikov, describing the assessment of area variations of Pamirs-Alay glaciers based on topographical maps as well as air and space photographs taken at different times (Schetinnikov 1998). In recent years, the number of assessments of glacial variations, based on ASTER satellite images has increased significantly (see, e.g. Batyrov & Yakovlev 2004; Karandayeva 2004; Aizen et al. 2006; Khromova et al. 2003). Almost all studies detected a decrease in the areas of the vast majority of glaciers of Kyrgyzstan. It looks like a rather reliable assessment of glacier volume through measurements has only been obtained for Ak-Shyirak ridge glaciers (Kuzmichenok 1989, 1990b; Kuzmichenok 1991).

Based on available reliable data on glacial variations in the region, we tried to assess the possible variations of the glaciated area of Kyrgyzstan from the time of publication of the Catalogue of USSR glaciers until 2000. It is a tentative assessment based on the simplest methodology. The results listed in table 5 are used as initial data.

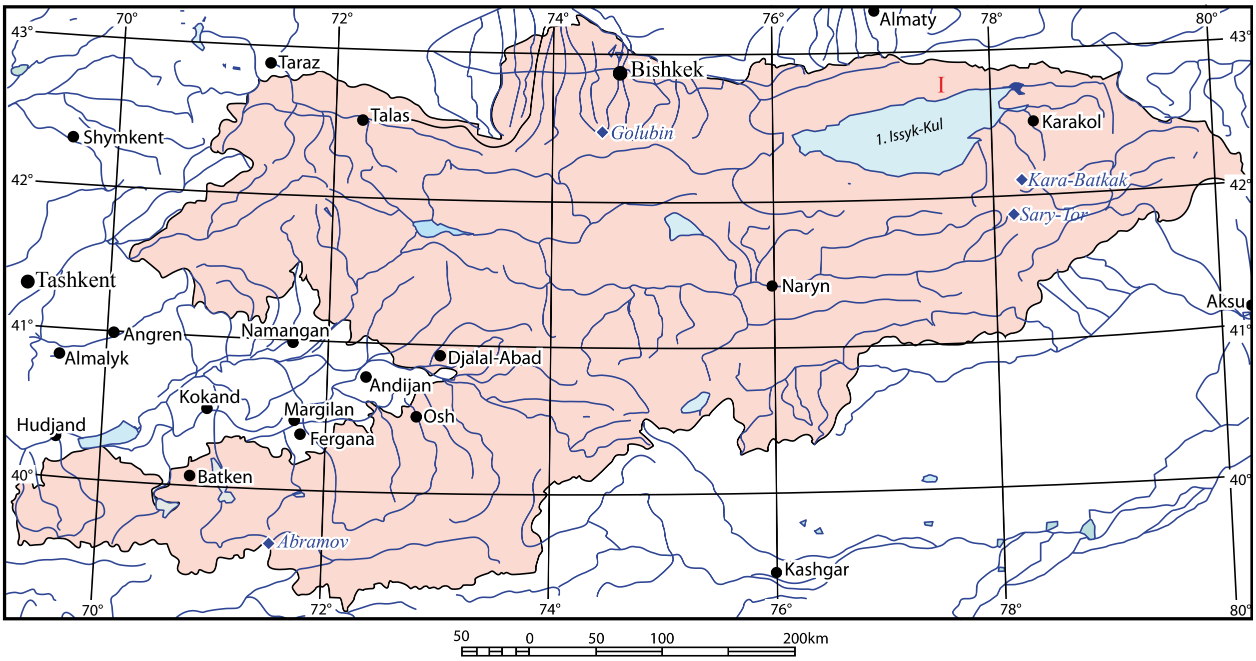

Figure 5 *The best studied glaciers of Kyrgyzstan.*

It should be noted, that not all the selected regions are within the territory of Kyrgyzstan. The chosen regions were selected, on the one hand upon the few reliable data sources available, and on the other hand, on the desire to cover the territory and range of elevations of Kyrgyzstan. It is well-known that the retreat of glaciers in the Tien-Shan and Pamirs-Alay suffered from some moderate reduction in the 20st century, which accelerated from the mid-1970s on. This conclusion is further confirmed by the graphs of the cumulative mass balances of key glaciers of the region, shown in figure 6.

Table 5 Initial data of the variations in glaciated areas in selected regions

Region	Area variations		Source
	Years	d (%)	
Ak-Shyirak ridge	1943 – 1977	–4,2	Kuzmichenok, 1991; Aizen et al., 2006
	1977 – 2003	–8,7	
Ala-Archa river basin	1963 – 1981	–5,16	Aizen et al., 2006
	1981 – 2003	–10,61	
Gyssary-Alay	1957 – 1980	–15,6	Schetinnikov, 1998
Pamirs	1957 – 1980	–10,5	Schetinnikov, 1998
Tuyksu glaciers	1958 – 1998	–20,2	Hagg et al., 2006
Glacier No. 1 (China)	1962 – 2003	–12,4	Ye et al., 2005

The data on the Golubina, Tuyksu, Kara-Batkak and Glacier No. 1 (Chinese Tien-Shan) were obtained from Glaciation (1995), data on the Abramov glacier came from Glazyrin et al. (1993), and on the Sary-Top glacier from Kuzmichenok (2002a). The graphs shown in figure 6, illustrate the glacial retreat rather convincingly and also suggest a rather abrupt aggravation of conditions for the glaciers in the region during the mid-1970s. This phenomenon was also found in a study published by Kuzmichenok & Kasenov (2002b) and in a study of variations in the Ak-Shyirak glaciers.

Therefore, it can be conditionally concluded that an enhanced abrupt acceleration of glacial retreat in the region began around 1975. Furthermore, it could be assumed that the rate of glacial retreat within the period before (V_1) and after 1975 (V_2) was constant. Then, based on simple arithmetical procedures an average ratio of V_2 to V_1 equal to 2.745 can be calculated for Ak-Shyirak glaciers and glaciers in the Ala-Archa river basin (see Table 5). It should be noted, that in Batyrov & Yakovlev (2004) a reverse ratio of these rates was computed for the Raigorodsky glacier located in the same region, while Narama et al. (2002) found a ratio similar to ours. Further, again based on simple arithmetical calculations, it is possible to obtain values of these rates for all regions selected earlier. These values, together with some approximate parameters of the regions are listed in table 6.

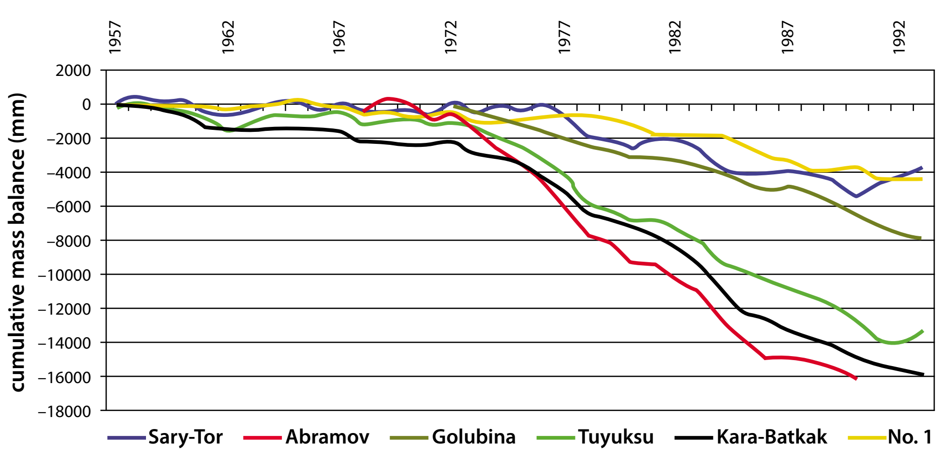

Figure 6
Cumulative mass balances of well studied Central Asian glaciers.

Table 6 Some information on selected glaciated regions

Region	B_m (°N)	L_m (°E)	H_{max} (м)	V_1 (%/year)	V_2 (%/year)
Ak-Shyirak ridge	41,8	78,3	5,1	−0,111	−0,326
Ala-Aracha river basin	42,5	74,5	4,9	−0,189	−0,482
Gyssary-Alay	39,7	71,5	5,7	−0,492	−1,350
Pamirs	38,0	72,5	7,5	−0,331	−0,909
Tuyksu glaciers	43,1	77,1	4,4	−0,252	−0,692
Glacier No. 1 (China)	43,1	86,8	4,3	−0,138	−0,379

B_m stands for mean latitude; L_m stands for mean longitude; H_{max} stands for maximum elevation; V_1 stands for the rate of glaciation area variations to 1975; V_2 stands for the rate of glaciation area variations after 1975.

Further, based on the least-squares method, we were looking to approximate the rates in the form of linear dependencies, dependent on various combinations of the glaciation region parameters listed in table 6. The root-sum-square uncertainties of the approximations are listed in table 7.

S stands for a root-sum-square uncertainty. The subscript of 0 specifies that this is a root-sum-square deviation of rates from their mean values at the initial sampling. The other subscripts specify arguments, used in the process of approximation.

The results presented in table 7 indicate rather convincingly, that the linear dependencies of the rates can be approximated by 3 parameters as follows:

$$V_1 = -8.65 + 0.15624 \cdot B_m + 0.00966 \cdot L_m + 0.22199 \cdot H_{max} \quad (4)$$

$$V_2 = -24.20 + 0.44176 \cdot B_m + 0.02434 \cdot L_m + 0.62385 \cdot H_{max} \quad (5)$$

Subsequently, based on equations (4) and (5) and the Catalogue of USSR glaciers, possible glaciation area variations in Kyrgyzstan were calculated individually upon each Section of the Catalogue. These calculations suggested for Kyrgyzstan a total glaciated area in 2000 of 6479.5 km², or –19.8 % of the initial area.

Table 7 Root-sum-square uncertainties of approximated rates (%/year)

	S_0	S_B	S_L	S_H	S_{BL}	S_{BH}	S_{LH}	S_{BLH}
V_1	0,130	0,096	0,091	0,111	0,067	0,046	0,077	0,029
V_2	0,481	0,259	0,252	0,302	0,188	0,122	0,218	0,082

Thus, it can be concluded that the total glaciated area in Kyrgyzstan since the Catalogue of USSR glaciers was prepared (usually in the 1950s–60s), could have decreased by about 20%. Based on the above value of glaciation area in Kyrgyzstan, and using the values in "Sovremennoe oledenenie" (1987), a rather credible picture emerges: between 1950–1960 the total glaciated area in Kyrgyzstan was around 8,100 km², between 1977–1980 around 7,400 km², and in 2000 around 6,500 km².

River Runoff Montitoring

Systematic observations of the river runoff in Kyrgyzstan were launched in 1911. Over the period from 1911–1915, the Alamedin and Sokh hydrological posts were operating. Later, observations were rehabilitated and have been under intensive development since 1925. According to Mamatkanov et al. (2006), the reference books "Major hydrological properties", published under the Soviet power, list the measurements of hydrological properties at 427 hydrological posts. The map "Surface Water" (Poverkhnostnye vody 1988) with a scale of 1:500000 shows the locations and data of 175 hydrological posts which could be used for summaries. We have already mentioned above, that in 1985 there were 149 hydrological posts operating at the same time. However, presently only 76 of them are operating. Naturally, hydrological posts that have a rather long series of observations and that are located above the area of runoff dispersion, where water is used for irrigation purposes, are of most interest. According to reference books (e.g. "Osnovnye gidrologicheskie kharakteristiki" 1967), there are 123 such posts.

The most comprehensive and updated source of information on the river runoff in Kyrgyzstan and its variations over time is a monograph (Mamatkanov et al. 2006). In particular, it specifies river runoff variations for two periods of time: since observations were launched up to 1972, and from 1973 to 2000. According to Mamatkanov et al. (2006), the average runoff of all the rivers in Kyrgyzstan until 1972 was 47.1 km³/yr. This value increases to 47.48 km³/yr if subsurface flow (according to our information, obtained through digital models of the precipitation conditions (Kuzmichenok 2003) is included. Over the period from 1973–2000, the average total river runoff in Kyrgyzstan was estimated at 50.0 km³/yr, a 6.2% increase. Mamatkanov et al. (2006) studied runoff variations before and after 1972 at 74 hydrological posts. 42 of them reported an increase of mean annual runoff, 30 reported a reduction and 2 reported a virtually unchanged runoff. It should also be noted, that linear trends of average annual water consumption in 7 rivers of Kyrgyzstan, presented in Mamatkanov et al. (2006), were positive in 5 of them. The increase in river runoff in some basins is often thought to be related to the degree of area glaciation (Dikih et al. 2002; Mamatkanov et al. 2006), as it is assumed that the runoff increase is caused by glacial retreat. While this may be the case, other possible factors should not be disregarded. Such factors may include variations in the total and distribution of precipitation and evaporation. figure 7 illustrates the assumed dependency between river runoff variations before and after 1972 and the degree of basin glaciation, according to Mamatkanov et al. (2006).

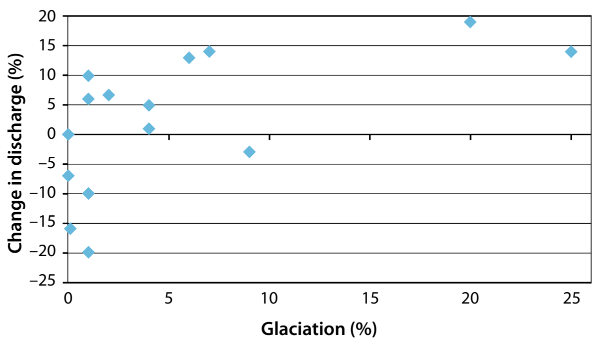

***Figure** 7 Dependency of runoff variations and degree of area glaciation for 15 hydrological basins in Kyrgyzstan (Mamatkanov* et al. *2006)*

The relationship shown in figure 7, does not seem to be as clear as could be expected. To further study the relationship, we calculated the distribution of the hydrological posts which reported a runoff increase or reduction (before and after 1972) by months, therefore identifying runoff increases caused by the melt of seasonal snow covers and glacial melting. This was done based on data, published in Mamatkanov et al. (2006). The results are shown in figure 8. The analysis indicates that, along with river runoff increases due to glacial melting (July), increases also happen as a result of increased melt water amounts from seasonal snow covers (March, April). Certainly, the results presented in figures 7 and 8 are also strongly dependent upon the initial sampling period used. However, it can be concluded that there are multiple causes for the river runoff increases in Kyrgyzstan over the past years.

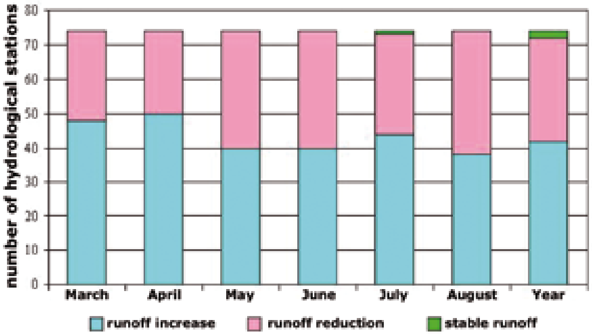

Figure 8 *Distribution of hydrological posts in Kyrgyzstan, based on the character of runoff variations before and after 1972*

It should be noted here, that some publications also advocate a different point of view, namely that the contributions of snow and glacial components to the river runoff of the territory bordering on Kyrgyzstan have decreased recently (Karandaev & Tsarev 2005). It is quite possible that, to some extent, such an "anomalous" conclusion was made due to a different definition of the term "glacial runoff". The aspiration (Glaciological dictionary 1984) to standardize this term as "a runoff of melt water from seasonal snow, firn and ice as well as liquid precipitations, supplied to the river network from glacial surface" might be correct from a purely geometrical viewpoint, but is hardly appropriate to interpret the glacial contribution to the annual (or long term) river runoff.

The viewpoint of Schetinnikov (1998) might be most appropriate and true to life. It reads as follows, "In our opinion, glacial supply to the rivers takes place due to melting of a long-term ice and firn stock: this is the major hydrological role of glaciers: to accumulate the annual excess of precipitations, re-distributing its melting in the long run".

However, we advocate the application of accumulative glacial mass balance values in the basin, when studying the reasons for long-term river runoff variations in high-mountain regions. In this theory, a zero glacial mass balance in the selected year will be defined as a zero contribution to the river runoff. In the event of a positive mass balance, some share of the precipitation should be subtracted from the annual total of probable river runoff; and in the event of negative mass balance, a certain value resulting from the increased melting of long-term ice stock, should be added to probable river runoff.

Main Conclusions

Upon the launch of perestroika and the collapse of the USSR, Kyrgyzstan saw an abrupt, sometimes even disastrous, reduction in the observation net monitoring climate variables, snow covers, glaciers, and river runoff. Remote sensing of the Earth from space seems to be able to only partially compensate for this loss. However, even this goal is hard to meet in Kyrgyzstan without some external assistance.

- It may be stated, that in recent years Kyrgyzstan saw an increase in average annual air temperature rates, mainly caused by global warming. It is likely that the optimized location of meteorological stations on its territory may ensure an adequate representation of the monitored properties throughout Kyrgyzstan. It is hard to establish fixed automatic meteorological stations in the little-inhabited high mountains of Kyrgyzstan because of reported acts of vandalism by locals, tourists and mountaineers.
- Variations in the total precipitation in Kyrgyzstan in the past years have not been as obvious as air temperature variations. On the whole, we may assume that the annual total of precipitation has slightly increased recently. However, it is quite evident that in order to carry out a more exact analysis, it would be necessary to either significantly increase the number of precipitation measuring stations, or to switch to studies of precipitation variations based on digital models of the entire territory and specifically developed mathematical models.
- The highly variable, both in extent elevation, snow cover of Kyrgyzstan, which has been supervised rather well over the past, is also subject to variations over time. It seems to be rather difficult to provide a reliable assessment of this variability. It is likely that in the future it will be necessary to use remote sensing methods of monitoring and to apply specifically devised digital and mathematical models.
- As for the glacial area in Kyrgyzstan, it may be stated that it is decreasing at least since the 1950s and this reduction has accelerated since the mid-1970s. We may regard the loss of a net of detailed glaciological measurements (especially glacial mass balance) as irreplaceable. It will be hard to even partially restore such a net for economic reasons. The only alternative to monitor the state of glaciers in Kyrgyzstan is through the remote sensing of the equilibrium

line altitude (ELA) (Ostrem & Brugman 1991) and the assessment of the glacial mass balance based on adopted statistical relationships.

- The river runoff of Kyrgyzstan has been monitored well recently. The preservation of approximately half of the operating hydrological posts, allowed the rather reliable identification of an increase in the total runoff of Kyrgyzstan rivers over the past 2-3 decades. To ensure further activities in this field, the net of runoff monitoring stations needs to be optimized. Further studies are needed to identify the reasons for runoff variations. These studies should be based on the net of hydrological posts, but also on digital precipitation models of inland Kyrgyzstan.

The author finds it to be his pleasant duty to express his sincere appreciation to V. Romanovsky (Institute of Water Problems and Hydropower of the Academy of Sciences of Kyrgyzstan) and I.Mayatskaya (Kyrgyzhydromet) for provision of initial data, required for the present study.

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Current and projected changes of glaciation in Central Asia and their probable impact on water resources

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In Central Asia snow and ice melt is an essential contribution to renewable water resources. An evaluation of possible changes due to climate change and its impact on water availability is important for water resources management. The paper presents regional trends and projections of the development of snow cover and glaciation.

Introduction

The rational usage of water resources is one of the main components of the current strategy of nature management and sustainable development at the national level. Increasingly, problems of the joint usage of transboundary water resources are the source for interstate conflict situations and the subject of increasingly complicated interstate negotiations. It can be stated with a high degree of certainty that natural flow resources in the Aral Sea region are fully exhausted and the economy of the region is developing under conditions of ever increasing water shortage. Even now overall usage of water resources in the Syrdarya basin amounts to 130 – 150 % and in the Amudarya basin to 100 – 110 % (Kipshakbayev & Sokolov 2002). Taking into account the current and predicted rates of population growth, the situation of drinking water supply per capita in the region will become even worse with time.

Under these conditions it becomes more and more obvious that the problem of water resource management in the Aral Sea basin is a vitally important problem. Its solution is not only a determining factor for the sustainable, ecologically balanced development of the region but also plays an important role in ensuring national and regional safety. Despite efforts by the local governments and the international community, the situation of adequate water supply for the population and the economy of the countries of Central Asia remains difficult and shows tendencies of getting even worse (Central Asia: Water and Conflict 2002; Severskiy 2004; Severskiy et al. 2006).

The problem becomes even more acute if one takes into consideration the unfavorable predictions of probable climatically driven future changes in water resources. These predictions forecast a reduction of the water resources of the main basins in the region by 20 – 40 % in the near future in the near future compared to the current state (Chub 2001).

Because of the already arid climate of Central Asia, such a reduction in water resources will inevitably necessitate a considerably reconstruction of the whole system of water usage and might cause large scale ecological and socio-economic problems. Taking into account the forecast increases in water consumption in the region, it is important to evaluate possible changes in the water resources for the near and far future. For the arid areas of the world this is a task of crucial importance: in the conditions of ever increasing water shortages any considerable further reduction in river runoff directly causes a decline in the economic activities of the countries of the regions, the deterioration of ecosystems and, sometimes, the deterioration of the sanitary-epidemiological situation, especially in the lower reaches of the river. These factors directly affect life quality and welfare of the population.

While anthropogenically driven changes in water resources (construction of new water storage reservoirs, increase in irrigated areas, etc.) can be calculated with a high degree of reliability, the estimation of probable climate driven runoff changes remains problematic.

It is evident that in order to predict changes in water resources, it is first necessary to project probable changes of climatic conditions along with climate driven changes of the main sources of runoff formation, mainly seasonal snow covers and glacier ice.

Research and Results

The overwhelming majority of the available models forecasting probable changes in water resources in the foreseeable future are based on assumptions about the changes in the water balance components in the runoff formation zones as a result of temperature growth caused by the increase in greenhouse gas concentrations in the atmosphere. An analysis of projections for various river basins all over the globe convinces us that existing models are not ideal: projection results obtained for the same basin with different models often differ quite substantially. Moreover, the idea of inevitable future global climate warming is not irreproachable (Kondratyev & Donchenko 1999; Schröder & Severskiy (Ed.) 2004; Severskiy 1999).

Climate change predictions

According to the estimates of the Intergovernmental Panel on Climate Change, the mean global temperature of the atmosphere has increased by 0.3 – 0.6 °C during last century (Climate change 2001). Connecting this process with the rising trends in the concentration of CO_2 in the atmosphere, the authors of numerous publications, including those concerning the territory of Kazakhstan, predict a significant warming trend in the coming decades. Furthermore, these studies forecast changes in the natural environment that are not favorable for the economy, and may result in significant economic losses (Chichasov & Shamen 1997; Chub 2001; Eskersepova et al. 1996). According to these predictions, available water resources of the main basins within Kazakhstan will decline by at least 20 – 22 %, the occurrence of droughts will sharply increase, and the grain crop productivity will decrease by 20 – 23 %. The scale of probable water resource changes obtained for the Aral Sea Basin using four well-known climate change scenarios is rather wide – from positive values (GFDL model) to a decrease in the Syrdarya River runoff by 25 % and in the Amudarya River runoff by 40 %. It is obvious that such a decrease in water resources would cause very serious consequences for the countries of the region.

Some questions about climate change seem to have been resolved as trends in the development of the climatic system are evident. Nevertheless, in a problem as complex as climate change not all is clear and understood. The most plausible causes are: Firstly, significant changes in natural landscapes over the past 50 – 60 years. The total area of nature affected by economic activities now exceeds 60 %. Around 1/5 of the earth (lands only) has actually been transformed considerably by economic activities and no longer can be considered natural according to the basic characteristics of the geographic zones to which the affected territories belong (Krenke 1989). During the 20th century, the changes in the environment progressed from a local to a regional and eventually to the global scale. Intensive degradation of natural landscapes is typical for the past 50 years. At present, areas not affected by economic activities amount to only 4 % of the entire territory of the USA. Europe (excluding Iceland and the Scandinavian countries) has no unaffected landscapes (Krenke 1989). The area covered by landscapes that dried up in the Nechernozemie of Russia totaled 6,300,000 hectares over the past 50 years. Furthermore, a man-made river network consisting mainly of irrigation and drain channels with a length that is five times more than the circumference of the earth was created during that time (Danilov-Danil'yantz et al. 1994; Losev 1986). Additionally, 90 % of all large water reservoirs in Russia were built during the same period. Obviously, this has some effects on the climate characteristics, especially air temperature, humidity, radiation, water balance, and atmospheric precipitation.

But the most probable reason for the established increase in air temperatures is a considerable change in the local conditions around the locations in which climatological observations are carried out. Meteorological stations generally were initially created outside populated areas. Nowadays, these locations are often inside of expanding cities (often even in the center of town, for instance Alma-Ata HMO and Tashkent Observatory). Naturally, differences in the observed climatological data that can be attributed to the influence of the surrounding populated areas are reflected in the readings of the observation stations. The warming effect of a town is a well-known fact. The city landscape considerably distorts the natural change of climate variables as the climatic character-istics of a town differ clearly from those typical for the surrounding area. The difference in air temperatures of a town compared to its surroundings can reach 5 – 6 °C for large towns. A comparative analysis of trends in air temperature and increase in population of the respective towns and villages leaves no doubt in t he well-defined monodirectivity of these processes: both the trends of the mean annual air temperature and population not only have a well-defined monodirectional character, but in a number of cases are close to parallel, indicating that the intensities of the processes have similar parameters (Severskiy 1990).

According to research, the size of the "thermal footprint" of a settlement, its configuration, and location does not remain constant and can change not only from month to month, but even within a week. Hence, the distortion of observations by a meteorological station due to the warming effect of the urban territories is not the same for each of the numerous stations of meteorological monitoring network. Rather, it depends on the site of the meteorological station in relation to the "thermal footprint" and to the sources of thermal pollution inside an inhabited area, and, furthermore, on the possible displacement of the "thermal footprint" due to changes in the synoptic conditions. The maximum difference of temperatures in populated areas compared to the surrounding territory grows with the size of the populated area and can exceed 8°C. It could be argued that the warming trends found for a number of Kazakhstan's meteorological stations likely do not reflect the real climatic changes, but rather are the result of the accumulation of distortions in the recorded temperature fields under the warming influence of urbanized territories. There are reasons to assume that the effects greenhouse gases have on climate changes are not as substantial as commonly assumed (Severskiy 1990).

It should further be noted that in Turkmenistan where the desert landscape has not changed significantly and where small settlements still dominate, the mean annual air temperature has increased by only 0.1 °C from 1931 to 1995 (Ibragimov 2004), while in the heavily populated regions of neighboring Uzbekistan where natural landscapes have practically disappeared during the same period it has increased by 2.0 – 2.5 °C. Thus, there are reasons to suppose that the data of many meteorological stations do not completely adequately reflect the real changes of the climate.

The exhibited increases in air temperatures can be attributed to various causes. Therefore, there might not be sufficient evidence to expect the predicted considerable warming in the near future.

Current and predicted changes of snow and ice and other renewable resources

In Central Asia snow and ice melt water contributes decisively to the formation of renewable water resources. Therefore, an evaluation of possible changes in water resources in the foreseeable future automatically implies the reliable prediction of the changes in snow and ice resources. The trends in the development of snow covers in the study region is more or less clear: according to analysis carried out in the Northern Tien Shan the average maximum snow water equivalent has not changed over the last decades (Pimankina 1998; Schröder & Severskiy (Ed.) 2004). Similar results were found for the Western Tien Shan and the Gissaro-Alay by Professor G. E. Glazirin (unpublished) and B. F. Tsarev (Artemjeva & Tsarev 2003). The long term averages of total river runoff have been steady as well (Chub 2001; Schröder & Severskiy (Ed.) 2004).

An evaluation of the dynamics of ice resources is more complicated. Several studies (Cherkasov 2002; Dikhich 2001; Dikhich et al. 2001; Shchetinnikov 1993, 1998; Shchetinnikov et al. 1994; Vilesov & Uvarov 2001) have simultaneously concluded, that the glacial systems of the Central Asian mountains are currently decreasing in size and volume at similar rates. For the last decades the area of glaciation in different regions of the Tien Shan, the Gissaro-Alay, the Pamir, and the Dzhungarskiy Alatau has decreased at an average rate 0.8 % per year (Cherkasov 2002; Cherkasov et al. 2002; Dikhich et al. 2001; Djurgerov (ed.) 1995; Shchetinnikov 1993, 1998; Shchetinnikov et al. 1994. Looking at these results, it could be suggested, that current and predicted future changes in the ice resources of the Central Asian mountains could be studied on the example of a single representative area that has reliable information on glacier dynamics. In Central Asia such an area is the basin of the Ili River, the main river in the Balkhash Lake basin. The transboundary basin of the Ili River includes the glaciated mountains of the Northern Tien Shan and the Dzhungarskiy Alatau in Kazakhstan, and the East Tien Shan and the Dzhungarskiy Alatau in the territory of China. The biggest glaciers are concentrated in the Chinese part of the basin. However, the Zailiiskiy-Kungei and Dzhungharskiy glacial systems, located within the limits of the Ili River basin in the territory of Kazakhstan, are rather typical for the glaciation of the entire region. Furthermore, the necessary, reliable information is available for exactly these glacial systems.

The degradation of the glaciers within those two systems can be documented over time using comparisons of the detailed glacier Catalogues (Glacier Inventories) produced on the basis of aerial photographs taken in 1956, 1972 (the Dzhungharskiy Glacier System), 1975, 1979, and 1990. This makes it possible to analyze the parameters of glaciation of the Ili-Balhash Basin glacier systems in 1956, 1972 (the Dzhunghar Glacier System), 1975 (the Zailiyskiy-Kungei Glacier System), 1979 and 1990 (the Northern Slope of Zailiyskiy Alatau glaciation).The resulting estimations of glacier area are given in table 1. According to these results, the glacier area of the Northern Tien Shan decreased at a rate 0.86 % per year during the period from 1956 to 1975. In the period from 1956 to 1979 the average rate of reduction was about 0.89 % per year. Over the entire period (1956 – 1990) the glaciated area on the Northern Slope of the Zailiyskiy Alatau decreased at an average rate of 0.85 % per year (Table 1). Table 2 lists the changes in total glacier area (pure ice) of the Dzhunghar glacier system for the period from 1956 to 1990. It becomes evident that mean annual rates of glaciation decline can be considerably different even in basins situated close to each other.

The spatial distribution of the rates of glacier decline is very indicative: while the average rate of decline equals 0.924 % per year, a maximum rate of 1.082 % per year can be determined for the Southern slope of the Dzhungharskiy Alatau. Minimal values of up to –0.716 % per year are characteristic of the Eastern parts of the mountains, such as the basins of the rivers Tentek and Yrgaity. Here, the influence of the topography and an increase in annual summer precipitation from western to eastern areas becomes evident (Severskiy et al. 2006). A comparative analysis of the rates of glacier degradation listed in Tables 1 and 2 indicates that lower degradation rates are characteristic of orographically closed basins of eastern orientation, such as the basin of

Table 1 Change of the glaciation area of the northern slope of Zailiyskiy Alatau for the period from 1956 to 1990

Author	Glaciation area, km²				Annual rate of glaciation reduction for the period, %					
	1956	1975	1979	1990	1956 – 1975	1955 – 1979	1975 – 1979	1975 – 1990	1979 – 1990	1955 – 1990
Cherkasov	271.2	240.4	228.2	204.7	0.568	0.661	1.269	0.990	0.936	0.700
Vilesov & Uvarov	287.3	—	229.0	203.5	—	0.846	—	—	1.012	0.833
Obtained	287.3	240.4	228.2	204.7	0.816	0.857	1.269	0.990	0.936	0.821

Table 2 Variation of total glacier area (pure ice) of the Dzhunghar glacier system for the period from 1956 to 1990

Region, river basin	Glaciation area, km²			Annual rate of glaciation reduction for the period , %		
	1956	1972	1990	1956 – 1972	1972 – 1990	1956 – 1990
Southern slope of the Dzhunghar Alatau ridge	242.1	194.1	153.0	1.239	1.175	1.082
Karatal River basin	214.6	176.0	149.1	1.123	0.846	0.895
Bien, Aksu, Lepsy River basins	312.3	245.3	218.6	1.342	0.603	0.884
Tentek and Yrgaity River basins	93.7	83.8	70.9	0.662	0.859	0.715
Dzhunghar glacier system as whole	862.7	699.2	591.6	1.185	0.854	0.924

Note: In 1990 glaciers with an area of less than 0.1 km² were taken into account. The area of glaciation in 1956 was determined from the Catalogue (Glacier inventory of the USSA 1967) using a coefficient K = 1.06 obtained as the ratio of glaciated area determined from 1:100,000 maps compared to that determined from 1:25,000 maps. The Southern Dzhungharia glaciation area was obtained by A.L. Kokarev and I.N. Shesterova using glacier boundaries outlined by P.A. Cherkasov on 1:25,000 maps.

Table 3 Change in the ice volume of glaciers of the Zailiiskiy-Kungei glacial system for the period from 1956 to 1990								
	Ice volume, km³				Average-annual rate of reduction of a glaciation for the period, %			
Region, river basin	1956	1975	1979	1990	1956–1975	1975–1979	1979–1990	1956–1990
Northern slope of the Kungei Ala-Too	(6.6)	4.34			1.802			
Chon-Kemin river basin	(6.7)	6.22			0.377			
Northern slope of the Zailiiskiy Alatau	(13.2)	11.34	8.83	8.43	0.742	5.534	0.412	1.032
Chilik river basin	16,04	16.96	13.73	12.76		4.762	0.642	0,584
Total	(42.5)	38.86			0.451			

Note: the values listed in brackets, are derived assuming a parity of volume and area of glaciers in the Zailiiskiy and Dzhungharskiy glacial systems.

Table 4 Change of ice volume of glaciers of the Dzhungharskiy glacial system for the period from 1956 to 1990						
Region, river basin	Ice volume, km³			Average-annual rate of reduction of a glaciation for the period, %		
	1956	1972	1990	1956–1972	1972–1990	1956–1990
Northern slope of a range	(11,1)	8.12	6.14	1.678	1.355	1.314
Karatal river basin	(9,8)	8.05	6.83	1.116	0.842	0.891
Biyon, Aksu, Lepsy river basins	(14,3)	12.1	10.03	0.962	0.950	0.878
Tentek, Yrgaity river basins	(4,3)	3.94	3.25	0.523	0.973	0.718
Total	(39.50	32.2	26.25	1.155	1.027	0.987

the Chilik River on the Northern Tien Shan and the Yrgaity River basin in the Dzhungarskiy Alatau.

The previous results once more confirm that it is not possible to determine representative glaciological regime characteristics using the observations from just one glacier, even from a “representative one” with a continuous observation record over several decades (such as the Tuyuksu glacier in the Zailiiskiy Alatau or the Shumskiy glacier in the Dzhunghar Alatau).The differences in the glacial regimes can not only be substantial, but may even have different signs.

Changes in glacier resources

Considerable differences are also evident in the degradation rates of glacier ice volumes as listed for several glacier systems in Tables 3 and 4.

It becomes evident, that the ice resources reduction rate does not remain constant either in space or time. The maximum rate of ice resources reduction in the Zailiyskiy – Kungeiskiy glacier system can be found on the Southern slopes of the Kungei Alatau ridge with an average degradation rate of 1.80 % per year for the period of 1956 to 1975 (Tables 3 and 4) while the average value for the entire glacier system during the same period equaled about 0.45 % per year. The period from 1975 to 1979 stands out sharply when looking at ice volume decline rates. The degradation rates surpassed 5.5 % per year on the Northern slope of the Zailiyskiy Alatau, while in the Chilik River basin a value of 4.8 % per year was obtained. This phenomenon could be attributed to observed positive anomalies of mean summer and annual air temperature during this period, along with abnormally small sums of summer precipitations. On the Tuyuksu glacier, the annual average accumulation during this period was about –84g/cm² which is almost 20 % less than the mean for the period from 1956 to 1974. Maximum losses of ice volume in the Dzhungarskiy Alatau during the period from 1956 to 1972 can again be seen on the Southern slope of the ridge where the degradation rates of ice resources were almost 1.5 times higher than those for the entire glacier system. The lowest rates of ice volume reduction in the Dzhungarskiy Alatau (0.52 % per year) were obtained for the glaciers of the orographically closed basins of the Tentek and Yrgaity rivers. In summary, the average rate of glacier area decline on the Northern slope of the Zailiyskiy Alatau was 0.85 % per year for the period from 1955 till 1990, while the corresponding figure for the net glacier ice volume reduction was about 1.0 % per year.

Future glacier resource changes

There are only few studies that attempt to predict the development of the glacier systems of Central Asia. According to these studies the glaciation of the Dzhunghar Alatau, the Northern and Central Tien Shan and the Caucasus could disappear by the end of this century (Cherkasov 2002; Dikhich 2001; Dikhich et al. 2001; Glacier inventory of the USSA 1967; Glazirin 1997; Golodkovskaya 1982; Vilesov & Uvarov 2001). However, it should be noted that the predictions for the near future are based on the extrapolation of average degradation rates of glaciated area and volume determined during the last decades or on the projections of climate changes, primarily in air temperature. As mentioned before, the rates of air temperature increase calculated from the observational data of regular climate stations are far from being representative for the true changes in climate. Accordingly, the forecasts of glaciation dynamics based on hypothetical (often arbitrarily given) rates of air temperature increase can be erroneous. It is also necessary to keep in mind, that the rates of glacier degradation obtained from repeated inventories of glaciers in the Zailiyskiy-Kungei and Dzhangarskiy glacier systems, as mentioned above, are not constant and, consequently, should not be used for extrapolations into the future.

It should also be noted, that according to a study by P. A. Cherkasov, which is based on the results of the dendrochronological analysis of Turkmen Archa sawings collected in the high-mountain belt of the Maliy Baskan River Basin (the Dzhungarskiy Alatau), there is a close correlation of the firn line height and the radial Archa increase.

The dendrochronological analysis shows a sharply pronounced cycle with a maximum duration of about 280 years. Taking this conclusion into account, it is possible to suggest that the degradation of the Dzhungarskiy Alatau ice resources will continue, albeit at a reduced rate, for at least 100 to 120 years. After this period a climate change towards more favorable conditions for the development of ice resources is possible. It should further be mentioned that L. R. Serebryaniy (Serebryaniy, Orlov & Solomina 1988), on the base of a glaciation dynamic analysis for the Sub-Atlantic period of the Holocene (with a duration of 3000 years), has concluded, that the Tien Shan climate will change towards more favorable conditions for the existence and development of glaciers in the near future.

Table 5 Projection of glacier volumes in the Ili River basin for the coming decades

Region	Volume of ice in glaciers, km^3					
	2000	2010	2020	2030	2040	2050
Kazakhstan's part of the Ili River Basin	35.04	32.91	30.08	27.50	25.14	22.99
Chinas part of the Ili River Basin	90.41	87.32	79.83	72.98	66.72	60.99
Total	125.45	120.23	109.91	100.48	91.86	82.98

If we take the current rates of decline of glacier area and volume as the basis for predictions of future conditions, the degradation of the Zailiyskiy Alatau glaciation over the coming decades can be expressed by the values listed in table 5. According to these values, the glaciation of the mountains of Central Asia will have reduced by only one third by the middle of this century and will not have disappeared by the end of the century as was previously suggested (Cherkasov 2002; Cherkasov et al. 2002; Dikhich 2001; Dikhich et al. 2001; Glacier inventory of the USSA 1967; Glazirin 1997; Golodkovskaya 1982; Vilesov & Uvarov 2001).

Future changes in water resources

The comparison of the results of repeated photogrammetric surveying of the Tuyuksu glacier allows some conclusions concerning the water resource changes of the region. The changes in the surfaces of the group of Tuyuksu glaciers during the period from 1958 to 1998 are illustrated in figure 1.

According to the data of figure 1, the ice thickness losses for most of the area were between 5 and 25 m.

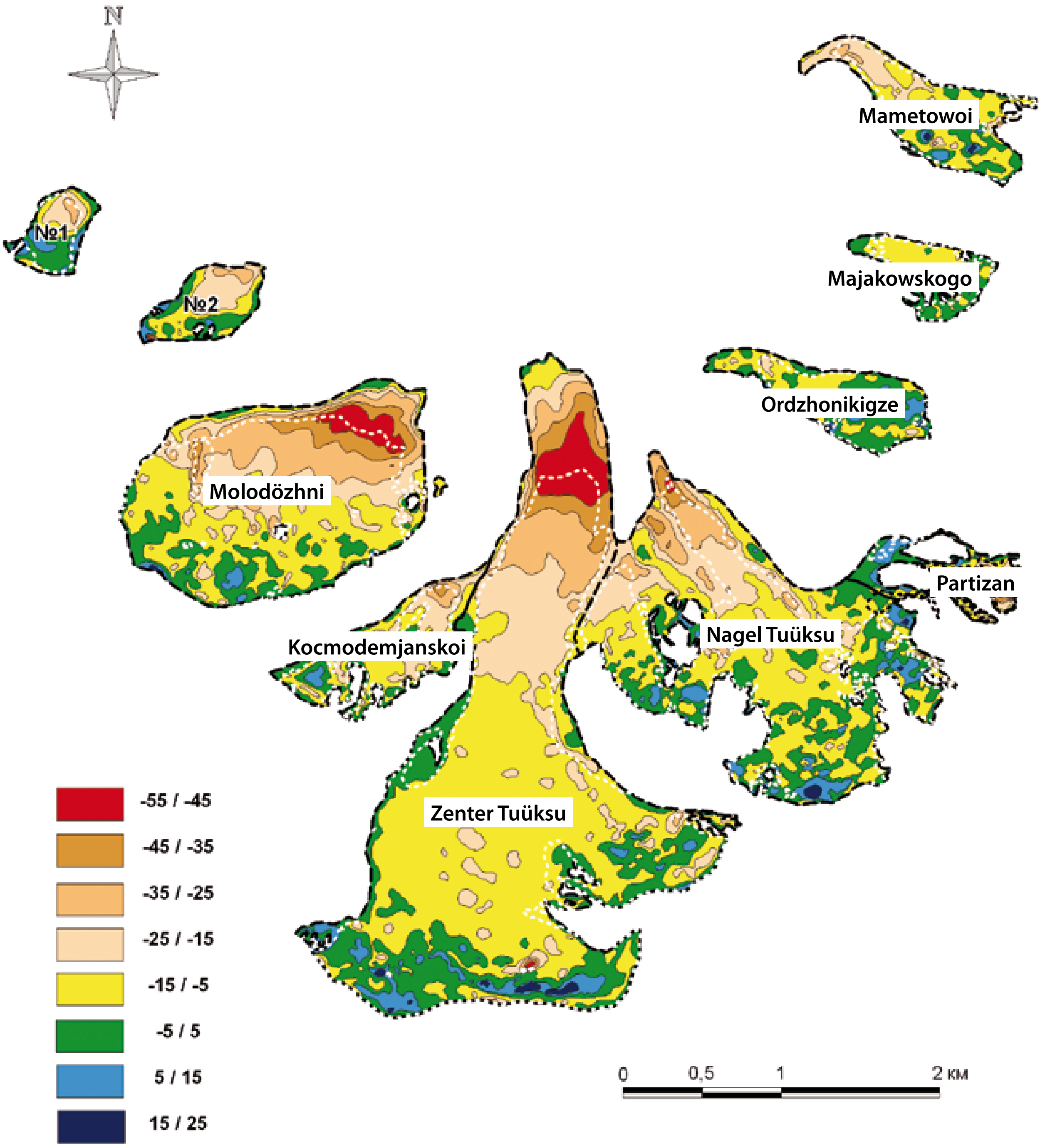

Figure 1 *Surface elevation change of the open part of the Tuyuksu glaciers during the period from 1958 to 1998 based on the results of the repeated photogrammetrical surveying.*

In the glacier accumulation zones (especially on small glaciers) the ice losses were close to zero (actual changes ranged mostly from 5 to –5 m). There were also quite sizeable areas especially at the glacier boundaries which had a positive mass balance with an additional accumulation of 5 to 25 m over the 40 years. This could indicate the possibility of a considerable deceleration of the glacier degradation processes during the last decade. Regional glaciation degradation rates provide further evidence for this possibility; they generally decreased from the beginning of the 1980s on and during the most recent years (beginning from 2000/2001) positive mass balances prevailed at the Tuyuksu glaciers.

The fact that in spite of the considerable degradation of glaciation combined with fairly steady mean annual sums of atmospheric precipitation and maximal winter snow water equivalents, the amounts of total runoff over the last decades did practically not change, indicates the presence of a certain compensating mechanism. Such a mechanism could be an increased contribution of melt water from thawing underground ice, in the areas of perennial permafrost as a result of climate warming. At least two findings support the existence of such a mechanism. According to the results of long-term geocryological studies carried out at the Zhusalykezen Pass (Northern Tien Shan, Zailiiskiy Alatau Range), the temperature of the permafrost ground increased significantly during the period of regular observations (1973 – 1996). Despite

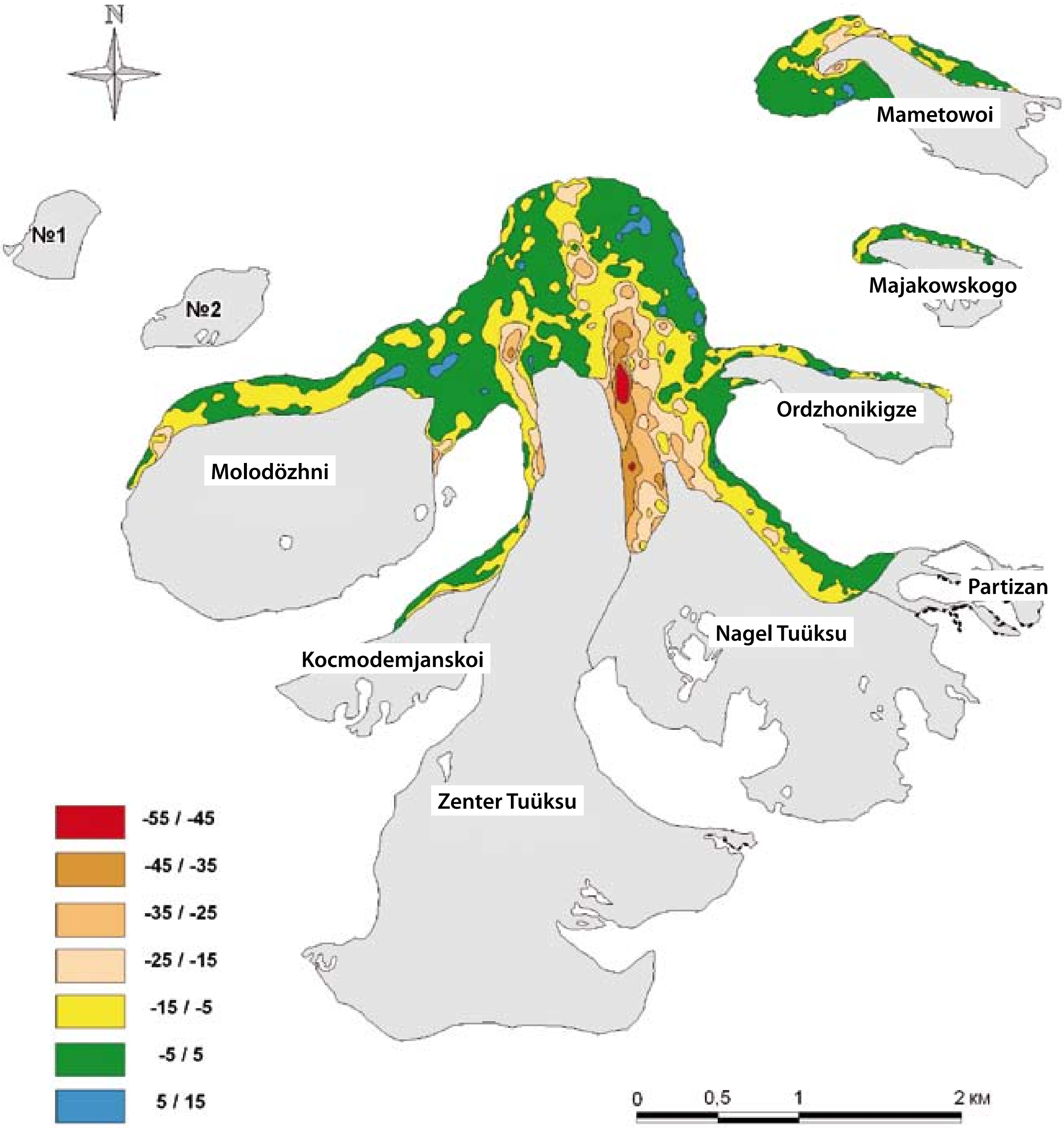

***Figure 2** Surface height change of the buried part of the Tuyuksu group of glaciers during the period from 1958 to 1998 (calculated from the results of repeated photogrammetric surveying)*

considerable interannual fluctuations, the general trend of the average annual temperature of the ground was clearly positive for the specified period. Additionally, increases in the depth of thawing and decreases in the thickness of the seasonally frozen layer were recorded in different natural settings of the Northern Tien Shan (Gorbunov et al. 1997). According to observations, the depth of the seasonal thawing of the ground in the boreholes at the Zhusalykezen Pass has increased by more than 1.1 m for the period from 1973 to 1996 (Gorbunov et al. 1997). Thus, for the specified period melt water from the thawing of a more than one meter thick layer of recently frozen ground could have contributed to the formation of runoff. Studies using isotopes to analyze the origin of runoff also confirm the existence of the mentioned compensatory mechanism. According to the results of the study, the lake-dam complexes of the alpine areas of Kyrgyzstan (Top-Karagai, Tuyuk-Tor, Kashka-Suu) can be attributed to 40 – 50 %, and in a number of cases even completely to the melting of buried moraine ice (Tuzova 2002).

figure 2 shows the surface height changes of the buried part of the above mentioned glaciers from the results of the repeated surveying. It becomes evident, that a considerable decrease of the ice thickness of the buried parts of the glaciers is characteristic for areas directly adjacent to the open ice part of the glaciers. Total losses of ice depth during 40 years ranged from 15 to 45 m for these areas. Surface height changes of buried ice for the remaining areas of the glaciers were between 5 to –5 m for the observation period. This indicates, that the buried ice remained at a more or less stationary state for the majority of the glacier area over the entire period. The total accumulated losses of ice volume of the buried part of the glaciers over the study period amounted to 0.0195 km^3 or 20.4 % of the total losses of ice of the open part of the Tuyuksu group of glaciers. This is a quite substantial value that, so far, has not been taken in consideration in water balance calculation. It can surely be assumed, that the melt water of the buried glaciers and rock glaciers compensate for a major part of the runoff losses connected with the decrease of the ablation area of the open part of the glaciers, providing stable runoff amounts despite glacier degradation. As the underground ice resources are approximately comparable to the ice resources of the modern terrestrial glaciation (Gorbunov &. Severskiy 1998, 2001) and assuming steady amounts of precipitation and snowfall, it is possible to assume, that even in the case of a continued intensive glacial degradation the runoff characteristics, including indices of intra-annual runoff distribution, will not change considerably in the coming decades. Further certainty in the prediction of virtually unchanged available water resources in the near future comes from the fact that more than 70 % of the total glacier runoff is formed from the melt of the seasonal snow cover on the surface of the glaciers and only about 30 % of total glacier runoff comes from the thawing of the age-old resources of glacier ice (Vilesov & Uvarov 2001).

According to long-term observations (Gorbunov &. Severskiy 1998; Marchenko 2003) in the region of the Zhusalykezen Pass (northern slope of Zailiyskiy Alatau, at an elevation of 3400 m) perennially frozen ground has thawed on average by 1.1 m during the period from 1973 to 1998. The melt water produced as a result of this thawing could have participated in

Table 6 Volume of melt water formed from the thawing of perennially frozen ground at the Small Almatinka River basin during the period from 1973 to 1996.

Interval of height, absolute m	Belt area, thousands of m^2	Volume of thawing ground, thousands of m^3 (assuming a thaw layer of 1.1 m)	Volume of melt water, thousand of m^3 (assuming an ice content of 30 %)	Volume of thaw ground at the zone of 3200 – 3500 thousands of m^2 (assuming a thaw layer of 1.3 m)	Volume of thawing ice, thousands of m^3	Volume of thawing water, thousands of m^3
3200 – 3500	2027	1115	335	1318	395	316
>3500	3241	3565	1070		1069	856
>3200	5268	4680	1404	4882	1465	1172

Note: The distribution of perennially frozen ground in the belt area calculation was taken from large scale maps prepared by German specialists, using the materials of photogrammetrical surveying of the year 1998. For this calculation, areas of open and buried glaciers as well as areas occupied by rocks were excluded. The thaw layers during the period indicated and the ice content of perennially frozen ground were taken from data of Gorbunov &. Severskiy (1998) and MARCHENKO (2003) using observational data from the Zhusalykezen Pass.

runoff formation. Estimations of the total volume of the melt water set free during the thawing of the perennial frozen ground during that period are listed in table 6.

The calculations of table 6 assume that at elevations between 3200 to 3500 m perennially frozen grounds occupy 50 % of the total area and that the thaw layer of the perennially frozen grounds during the study period considered was 1.3 m. Thus, during the study period, a total runoff of 1,170,000 m³ originated from the thawing of perennially frozen ground. It is necessary to keep in mind that, as mentioned, the state of the major parts of the buried glaciers did not considerably change from 1958 to 1998 (Figure 2). The total sum of melt water originating from the thawing of the buried parts of the Tuyuksu group of glaciers can be quantified at 1,200,000 km³. It is possible to assume that at the boundaries of the buried parts of the glaciers, the perennially frozen grounds of moraine depositions thawed by 1.1 m during period of 1973 to 1993. In this case, the volume of the resulting melt water would have been about 320,000 m³ and the total volume of melt water contributing to discharge from the thawing of perennially frozen grounds above an elevation of 3200 m would not have exceeded 1,500,000 km³, i.e. 65,200,000 m³ per year. This is only about 6.5 % of the average volume of annual discharge formed from the melt of glacier ice from the open ice parts of the Tuyuksu glaciers during the period of 1958 – 1998. Thus, it can be concluded that the compensatory runoff, in spite of expectations, originates not from the thawing of perennially frozen ground but from the thawing of ice in the buried parts of the glaciers and rock-glaciers.

It should also be noted, that the contribution of melt water from glaciers and the thaw of perennially frozen ground does not remain constant from year to year and depends greatly on the peculiarities of the local thermal regime and on snow conditions. During warm years when the temperature of the ground is relatively high and seasonal frost penetration is not deep, the contribution of melt water from the glacial-nival belt to the discharge of the following spring and summer is negligible. During years when the temperature of the frozen ground is lower, a portion of the melt water actually penetrates the bedrock, refreezes and stays frozen until the end of the ablation period, creating transit resources of water. During such years water balance values of the glacial-nival belt will be negative. These “preserved” water resources can contribute to runoff during the following years, causing initially confusing positive water balance values. As years of above and below average snowfall and air temperatures have a tendency to group into periods of 2-4 years in succession, the duration of periods of negative or positive water balance values is on average 3 years.

Conclusions

There are reasons to assume that the considerable warning trends established on the basis of climatological observations do not reflect the real climatic changes, but are rather the result of distortions in the temperature field recorded at climate stations over time under the warming influence of expanding urbanized territories. An indirect confirmation of this assumption is the known fact, that the warming is mostly attributed to an increase in the air temperatures during the winter (heating) season. For example, the increase in air temperatures in the North of Russia is 1.4 – 1.5 times higher during the cold period compared to the warm period. Furthermore, the present day warming reflects a natural trend in cyclic climate variations and the role of anthropogenic influences in this process is not as great as is commonly assumed. Hence, there is not enough evidence to believe the predicted considerable (2 – 4 °C) warming in the coming decades.

At the same time, it cannot be denied that we are currently witnessing a slow increase in air temperatures. The consequence of this process is a considerable reduction in the glacier resources of the mountainous countries of Central Asia. According to scientific explorations glacier resources in the Tien Shan mountains decline at the rate of 0.85 % per year by glacier area and of 1.0 % per year by volume over the last 35 – 40 years of the 20th century. It is expected that this process will continue for at least 100 years. Considering the natural cycles of climate fluctuations, it is possible to assume that in the foreseeable future (for the considered region not earlier than in about 100 years), the climatic conditions will change to more favorable ones for the existence of glaciers. Considering the stable precipitation amounts and, especially, the stable maximum snow water equivalents, it can be concluded that the regions glaciers and underground ice will not disappear completely during this century. Thus, the predominant opinion about the inevitability of the disappearance of the glaciers in the Tien Shan mountains and in the neighboring countries of Central Asia cannot be accepted.

Maximum snow storage as the main component of the snow resources was virtually unchanged over the last 40 years. The average runoff amounts of the major rivers have not changed either. The fact that in spite of a considerable reduction in glacier resources, the flow rates of the main rivers practically have not changed over the last decades suggests some compensating mechanism. Such a mechanism could be the increased flow of melt water from the thawing of underground ice, including ice accumulated in the perennial permafrost. Until now this circumstance has not been studied thoroughly. Taking into account the extreme importance of predicting probable changes in water resources as a reaction to climate change, this aspect deserves special attention.

The forecast significant decline of the water resources over the coming decades as a result of the anthropogenically caused warming of the climate, are scarcely probable. There is no sufficient evidence to fear the projected, significant climate warming and the corresponding decline of the water resources and predicted economic losses. Though this optimistic conclusion gives us a chance to predict the development of the situation in the near future, it does not make the problem less acute: water shortage in the region is one of the limiting factors of its sustainable development. At the same time the transboundary nature of the regional water resources is one of the main reasons for the necessary development of international processes in Central Asia. An analysis of the situation in the region leaves no doubt, that there is no alternative to exploring ways of a coordinated inter-state management of regional water resources.

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Distribution and changes of glacier, snow and permafrost in China

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This paper provide an overview of the current status of the cryosphere in China and its change. We first summarized the up-to-date statistics of the cryosphere in China based on the most recent available data. There are 46,377 glaciers in China, covering an area of 59,425 km^2. The glacier ice reserve estimation is about 5600 km^3 and the annual glacier runoff is about $61.6 \times 10^9 m^3$. The steady snow cover extent in China is about $3.5 \times 10^6 km^2$ and the maximum snow water equivalent is $95.9 \times 10^9 m^3$. The permafrost area in China is about $1.72 \times 10^6 km^2$. The total ground ice reserve in the Qinghai-Tibetan Plateau is about 10,923 km^3. We then reviewed some recent investigations of cryospheric change in China. The glacier areas in China have shrunk about 2~10 % for different types of glacier since 1960s. As a total, glacier recession is about 5.5 % from 1960s to the beginning of 21 century. Snow mass has a slight increase. The permafrost is in a significant degradation, with many evidences showing permafrost area shrinking, lower limit of permafrost elevating, ground temperature increasing, active layer deepening, and seasonal frost depth thinning. We also presented some model prediction of future cryospheric change in China. The glacier area shrinkage could be up to 26.7 % in 2050, but glacier runoff will increase until reaching its maximum in about 2030. The snow might show a increase trend in west China but decrease trend in east China, with interannual fluctuation varies more strongly. The permafrost will be in further degrading, 1/3 to half of the permafrost on the Qinghai-Tibetan Plateau will be degraded. Most of the high-temperature permafrost will disappear. The permafrost in northeast China would retreat rather northward.

Introduction

The cryosphere, as an integral part of the global climate system, plays a significant role in the energy and water cycle of the Earth's surface. It is usually considered as an indicator of global change because the frozen part of the Earth's surface, i.e., snow, glacier, sea/lake/river ice, permafrost are more sensitive to climatic change than other components of land surface. The cryosphere is also an amplifier of climatic warming because the temperature rise in cryospheric regions is generally larger than that in other regions and the positive feedback of cryosphere to climate system can enhance the climatic warming (Cheng 1996; Allison et al., 2001; IPCC, 2007).

China has a vast expanse of cryosphere which contains a large portion of the world's middle- and low-latitude mountain glaciers. China's permafrost area ranks third in the world and is first in terms of the middle- and high-altitude permafrost area. In particular, the Qinghai-Tibet Plateau (QTP) plays a very important role in global change. Recent investigations show the cryosphere in China is experiencing rapid change, with glacier retreating, permafrost degrading, environment in cryosphere regions becoming more variable, and hazards increasing (Jin et al., 2000; Kang et al., 2004; Qin et al., 2002; Shen, 2004).

In this paper, we will first introduce the basic statistics of major components of the cryosphere in China in the next section. Then, the recent findings of cryospheric change are described in section 3. In section 4, some predictions of future cryospheric change in China are presented. Section 5 is a short summary of the paper.

Cryosphere in China

The cryosphere in China is mainly composed of mountain glaciers, latitudinal and altitudinal permafrost, and snow. The sea, lake, and river freezing also occurs in north China and the QTP, but with relatively insignificant impact to the environment.
The up-to-date statistics of mountain glaciers are derived from the Chinese Glacier Inventory (CGI), which was accomplished in 2002 (Liu et al., 2000; Shi 2005), and the Chinese Glacier Information System (CGIS), which was established in 2004 (Wu and Li, 2004). The CGIS can be considered as a modified CGI, in which a strict quality control was conducted, glacier distribution from the attached maps of CGI and from topographic maps was digitized, and some editing errors in CGI were corrected. According to CGIS and the Concise Chinese Glacier Inventory, there are 46,377 glaciers in China, covering an area of 59,425 km². The total ice reserve is estimated using some empirical relationships established by regression analysis of the glacier areas and radar-measured glacier depths (Liu and Ding, 1986). The total ice reserve of the mountain glacier in China is estimated to be about 5600 km³. Converted to water, the amount is 5040×10^9 m³, which is about 5 times of the annual runoff of the Yangtse River (960×10^9 m³). Glacier runoff is a very important water resource in the arid regions of northwest China. Its annual amount is about 61.6×10^9 m³, accounting for 24.3 % and 8.7 % of the annual runoffs of inland rivers and outflow rivers in west China, respectively. For total river runoffs in west China, it accounts for 11.9 % (Kang et al., 2004).

A long time series dataset of snow depth and snow water equivalent (SWE) from 1978 to 2005 in China was developed using the passive microwave remote sensing data including the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I) (Che and Li 2005; Che 2006). According to the statistics derived from the dataset, the maximum snow distribution in China occurs in between later February and early March and the corresponding annual SWE is about 80.6×10^9 m³. Regarding the statistics for major snow zones, the maximum SWE is about 17.8×10^9 m³ in Xinjiang and the western part of Inner Mongolia, 41.9×10^9 m³ in the QTP including the Pamirs and the Qilian Mountains, 36.2×10^9 m³ in northeast China. The maximum snow distribution occurs in March, middle January, and later February in the three zones, respectively. The summation of the maximum SWE in the three major snow zones of China is 95.9×10^9 m³, which is about 10 % of the annual runoff of the Yangtse River. The mean snow cover extent is about 8.9×10^6 km² and the steady snow cover extent (with snow cover exists for more than 60 days) is about 3.5×10^6 km² (Che, manuscript in preparation: Snow water resource in China derived from long time series passive microwave remote sensing). The above statistics are close to those derived from an early study (Kang et al., 2004). The annual snowfall recharge was estimated to be over 345×10^9 m³ (Li, 1988), however, this value needs to be reevaluated by using both remote sensing data and in situ observations.

The permafrost area statistics are different in published literatures (Jin et al., 2000; Qiu et al., 2000; Zhou et al., 2000). According to an up-to-date permafrost map of China – the Map of the Glaciers, Frozen Ground and Desert in China (Wang et al., 2006), the permafrost area in China is about 1.72×10^6 km² and the seasonal frozen ground (not including the short time frozen ground) area is about 5.21×10^6 km². They totally occupies 72 % of China's land territory.
Most of the permafrost in China is altitudinal permafrost, distributed on the QTP and other mountainous areas. The area of altitudinal permafrost is approximately 1.36×10^6 km². The ice reserve in permafrost is huge. Nan (2003) estimated the ice volume in permafrost on the QTP. According to his calculation, the average thickness of permafrost is 61.5 m and the total ground ice reserve is about 10,923 km³, which is approximately two times of the total glacier ice reserve in China.

Cryospheric Change

Change of glaciers

The glacier change in the last few decades in China has been investigated by many Chinese glaciologists. Results showed that glacier recession is a commonplace but varies spatiotemporally. The area shrinkage is significant in the Himalaya area (Ren et al., 2004; Qin et al., 2000; Jin et al., 2005), Qilian Mountains (Liu et al., 2002), and Tianshan Mountains (He et al., 1999; Shi, 2000; Liu et al., 2006), where the area recession is about 5 – 10 % in the last 30 years. The glacier variation keeps almost steady in the hinterland area of Tibetan Plateau, where the recession of glaciers is very small (Li et al., 1999; Lu et al., 2002; Liu et al., 2004). But in recent year, the glacier shrinkage is speeding up in almost all the China's mountainous areas (Shi, 2001).

Table 1 Typical changes of glacier area in China

Study area and location	Data used	Period	Glacier number	Area (km²)		Area change (%)	Reference
				early time	later time		
Pumqu River basin, Himalayan region	Topographic map (1970, 80s), and ASTER and CBERS (2001)	1970s – 2001	999	1462±9	1330±8	−9.0	Jin et al., 2005
Poiqu River basin, Himalayan region	Topographic map (1970, 80s), IRS 1D-LISS 3 (2000, 2001)	1970s – 2000	153	236.8	231.6	−2.2	Wu et al., 2004
Rongxer River basin, Himalayan region	Same as above	1970s – 2000	200	334.3	324.1	−3.1	Wu et al., 2004
Glacier Reqiang, Xixiapama Mt., Himalayan region	MSS (1977 & 1984), TM (1990 & 1996), ETM+ (2000), ASTER (2003)	1977 – 2003	1	6.92	5.34	−22.9	Che et al., 2005
Glacier Jicongpu, Xixiapama Mt., Himalayan region	Same as above	1977 – 2003	1	20.28	18.81	−7.29	Che et al., 2005
Gangrigabu range, southeast Tibetan Plateau	Topographic map (1980), CBERS (2001)	1980 – 2001	88	797.78	795.76	−0.25	Liu et al., 2005
Xinqingfeng ice cap, Northern Tibetan Plateau	Aerial photograph (1971), ETM+ (2000)	1971 – 2000	64	442.7	435.3	−1.67	Liu et al., 2004
Malan ice cap, Northern Tibetan Plateau	Same as above	1971 – 2000	65	247.08	248.14	+0.43	Liu et al., 2004
Tarim basin	Topographic map (1960, 70s), TM/ETM+ (1999 – 2001)	1963 – 1999	3081	9998.5	9542.3	−4.6	Liu et al., 2006
Muztahgata Mountains (38°00´–38°40´ N 74°40´ – 75°40´ E)	Aerial photograph (1965), ASTER (2001)	1965 – 2001	128	377.21	373.04	−1.11	Cai et al., 2006
Karamilan-Keriya River, Tarim basin (35° – 40°N, 80° – 85°E)	Topographic map (1970s), TM/ETM+ (1999 – 2001)	1970 – 2000	895	1374.18	1334.91	−2.86	Xu et al., 2006
Daxueshan Mt., West part of Qilian Mountains	Aerial photograph (1956), TM (1990)	1956 – 1990	175	162.8	155.1	−4.7	Liu et al., 2002
Aemye Ma-chhen Range, upper reaches of the Yellow River	Aerial photograph (1966), TM (2000)	1966 – 2000	57	125.50	103.80	−17.3	Lu et al., 2005
Geladandong, upper reaches of the Yangtze River	Aerial photograph (1969), TM (2000)	1969 – 2000	70	899.31	884.4	−1.7	Lu et al., 2005 Lu et al., 2002
Yurungkax River, west Kunlun Mountains	TM (1989), ETM+ (2001)	1989 – 2001	42	N/A	N/A	−0.5	Shangguan et al., 2004
Muztag Ata-Kongur Tagh, the Pamirs	Aerial photograph (1962 – 66), ASTER (2001)	1962/ 1966 – 2001	379	1092.7	1025.8	−6.2	Shangguan et al., 2005

Note:

(1) In the column "data used", the original data used instead of the CGI are indicated. The glacier parameters in CGI are usually derived from the aerial photographs from 1960s to 1980s.

(2) They are some overlaps of glacier change in Tarim basin, Muztahgata Mountains, and Karamilan-Keriya River of Tarim basin.

(3) Acronyms. ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer. CBERS: China-Brazil Earth Resource Satellite. ETM+: Enhanced Thematic Mapper Plus. IRS 1D-LISS: Indian Remote Sensing satellite serie s 1D, Linear Imaging and Self-scanning Sensor. MSS: Multispectral Scanner. TM: Thematic Mapper.

Table 2 Glacier change from 1960s to 2000 in China

Glacier type	Area (km^2)		Decrease area (km^2)	Area change (%)
	1960s	2000		
Extreme continental type	19137.73	18685.54	452.19	2.4
Sub-continental type	27008.18	25390.53	1617.65	6.0
Maritime type	13254.16	12076.28	1177.88	8.9
Total	**59400.07**	**56152.35**	**3247.72**	**5.5**

Note:
The total area is a little different to that in Section 2 because different data sources are used.

In table 1, the recent investigations on the area change of glacier are summarized. Most of the findings were conducted by using remote sensing data.

Kang et al. (2004) extrapolated the area change to all glaciers in China (Table 2). As a total, China's glaciers have shrunk 5.5 % since 1960s to date.

Change of snowcover
The variation of snow in China is more complex compared to those of glacier and permafrost. Therefore, its diagnostic analysis is more difficult, not so much work has been carried out.

Chen used station data to analyze the snow variation on the QTP and showed that there is a jump from poor snow to rich snow in 1970s on the QTP (Chen and Wu, 2000).

Li (1999) revealed that in northwest China, the snow cover did not experience any decrease since 1987. The data used included SMMR snow charts, NOAA weekly snow cover chart, and snow data from selected metrological stations in west China. Li's finding is further verified by Qin et al. (2006). Their results showed that the long-term variability of western China snow cover is characterized by a large interannual variation superimposed on a small increase trend over the period between 1951 and 1997. No abrupt change in snow cover was found. Large interannual oscillation is the most striking feature over the QTP, and annual amplitude has increased since 1980s.

These conclusions are consistent with the results of Ke and Li (1998), Che and Li (2005), and Che (2006). However, Che (2006) believed that an analysis of longer time series of snow data derived from remote sensing data is needed for diagnostic of changing trend of snow in China.

The change of snow melting season is another important problem that should be take into account. However, we did not find any published literatures addressed this issue.

Change of permafrost
China's permafrost, especially the altitudinal permafrost which is mainly distributed on the QTP, is sensitive to climatic warming. Significant permafrost degradation has occurred and is occurring in most permafrost regions in China. The seasonal frozen ground is also diminishing in area and decreasing in depth of frost penetration. In this section, we introduce the evidences of permafrost area shrinkage, elevation of lower limit of permafrost, ground temperature increase, deepening of active layer, and thinning of seasonal frost depth.

Area shrinkage and lower limit elevation
A preliminary estimate for the areal reduction of permafrost on the QTP is $0.1 \times 10^6 km^2$ from 1970s to mid-1990s (Wang, 1997). Observations showed that along the Qinghai-Tibet highway (QTH), the southern lower limit of permafrost has moved 12 km northward, whereas the northern lower limit has moved 3 km southward. According to the 1:100 000 island permafrost map compiled in 1975, for the southern QTH (with a width of 2 km on each side of the QTH), the permafrost area was 64.8 km^2 in the counted area of 320 km^2, or about 20 %. The permafrost areas were divided into four groups according to geomorphic locations. Recently, comprehensive investigations indicate that the permafrost area has decreased to 41.7 km^2, suggesting a reduction of 35.6 % in the island permafrost area (Wang, 1997; Wang et al., 1996; Wang et al., 2000; Jin et al., 2000).

Investigation using ground penetration radar (GPR) provides more detailed evidence. Nan et al. (2003) conducted a GPR survey in the Xidantan, QTP in 2002. They found the permafrost area in the region has diminished to 141.0 km^2 from original 160.5 km^2 in 1975, displaying a shrinkage of about 12 %.

In northeast China, permafrost degradation is more severe because ground temperature is usually high in this region and human activities such as deforestation is strong.

Table 3 Changes of the MAGTs along the Qinghai-Tibet highway (Wang et al., 2000; Jin et al., 2000)

Borehole	JXG	CK114	CK124-4	Ck123-4	CK-7	K2956	No.1	CK123-7
Location	Xidantan	Taoerjiu	Valley	Basin	Tongtian	Cumar	FHS	Basin
Permafrost zone	northern lower limit	Continu-ous/island permafrost boundary	southern lower limit	season-ally frozen ground	river taliks	continuous permafrost	continuous permafrost	island perma-frost
Present MAGT	0.3	0.8	0.8	0.8	0.8	–0.9	–2.8	–1.0
Rise from 1970-1990s	0.5	0.3	0.3	0.3	0.4	0.1	0.2	0.2

Note: The MAGT here is defined as the mean annual ground temperature at about 15 m.

Many permafrost islands have disappeared in the island permafrost zone in the southern part of the Da- and Xiao-Xing'anling Mountains, where MAGTs range from –0.5 to +0.5 °C, and the thicknesses of permafrost vary from 5 to 15 m. Investigations showed that in one of the forestry bureau in the Xiao-Xing'anling Mountains, the areal percentage of permafrost has decreased from 10.5 % in 1957 to 0.05 % in 1980 and the degradation is closely related with the deforestation activities. According this rate of deforestation and subsequent permafrost degradation, permafrost must have completely thawed in this forestry bureau area. The distributions of island permafrost in other sites have also degraded substantially during the past 30~40 years (Jin et al., 2006).

Observations showed that on the QTP, the lower limit of permafrost elevated 40 to 80 m from 1970s in different regions (Wang et al., 2000). In Xidatan, the lower limit of permafrost elevated 25 m from 1975 to 2002 (Nan et al., 2003).

Borehole monitoring

Monitoring along the QTH from Golmud to Lhasa indicated that mean annual ground temperature (MAGT) is experiencing an increase of about 0.3 – 0.5 °C in seasonal frozen ground, taliks, and island permafrost zones, and about 0.1 – 0.3 °C in the continuous permafrost zones (Wang et al., 2000; Jin et al., 2000). See table 3 for monitoring at some selected sites.

It is recently found that the temperature of permafrost (at 6 m depth) is increasing with a rate of 0.05 °C/yr and 0.02 °C/yr in the low- and high-temperature areas on the QTP, respectively (Wu et al., 2005).

Active layer

A remarkable thickening at active layer of permafrost was observed on the QTP. The cold region engineering, i.e., maintenance of the QTH and construction of the Qinghai-Tibet railroad (QTR) provide an unique opportunity to observe the permafrost change along the roads. Many monitoring systems were established. Wu and Liu (2004) and Wu et al. (2005) analyzed the temperature data collected from 1995 to 2004 at 11 sites in the permafrost area along the QTH and QTR and found the active layer thickened obviously, particularly at the high-temperature permafrost area. They concluded that at low-temperature permafrost area, the thaw penetration deepened 3.1 cm/yr averagely, whereas at the high-temperature permafrost area, it deepened 8.4 cm/yr averagely.

Active layer thickening is even sharper in northeast China. The maximum thaw penetration depth at a wetland site in the Daxing'anling Mountains was 50~70 cm during 1960s~1970s. However, it increased to 90~120 cm or greater during the 1990s. At Yitulihe Permafrost Observatory, the maximum thaw penetration increased by 16 cm during the 3 year period from 1996 to 1999, with an average rate of 5.3 cm per year (Jin et al., 2006).

Seasonal freezing

The freezing depth is an operational observation by meteorological stations, which is measured once every day during the freezing-thawing period by reading the upper and lower depths of the distilled water filled in standard frost tubes.

Zhao et al. (2004) investigated the freezing depth change at 50 meteorological stations on the QTP from

1967 to 1997. They found that the depth of seasonal frozen ground thinned about 22 cm in the inland of QTP, with a mean annual decreasing rate of 0.71 cm. In northeast QTP, the depth of seasonal frozen ground thinned 21 cm, with a mean annual decreasing rate of 0.7 cm. In northwest and southeast QTP, the decrease of seasonal frozen ground depth is not so significant, thinned 6 cm and 5 cm in 30 years, respectively.

Wang et al. (2005) also summarized the change of seasonal frozen ground depth at 16 meteorological stations in Qinghai Province. The mean value of frozen depth was 144 cm in 1961 to 1970, but decreased to 124 cm in the period 1990 to 2001.

Wang et al. (2005) selected 19 stations in Xinjiang for analyzing the variation of seasonal freezing from 1961 to 2002. The mean and maximum frost penetration depths have thinned significantly with decreased values ranging from 7 to 37 cm. The freezing-thawing period has also shortened. The freezing date have lagged 4 days and the thawing date move up 5 days.

Predictions of Future Cryospheric Change

Glaciers

It is predicted that China's mountain glaciers will experience a quick recession under a warming climate scenario. According to Shi (2001), most of the glaciers with their area less than 1 km² will disappear before 2050. More detailed prediction of glacier change for different glacier types are summarized in table 4 (Shi, 2001; Kang et al., 2004). However, glacier runoff will increase because the glacier melting is accelerating (Shi, 2001; Xie et al., 2006). Xie et al. (2006) used a systematic model to simulate future change of glacier runoff. According to their suggestions, the total glacier runoff in China was $61.6 \times 10^9\,m^3$ in 1980s and was $66.0 \times 10^9\,m^3$ in 2000. If future air temperature rises in a rate of 0.02 k/yr or 0.03 k/yr, the glacier runoff will increase continuously from 2000 to 2030, and will reach its maximum value of $67.5 \times 10^9\,m^3$~$70.8 \times 10^9\,m^3$ in about 2030. After that, the glacier runoff is potentially to show a decrease trend, but till 2050 the runoff is still larger than that in 2000.

Snowcover

Li Peiji (in: Qin, 2002; Kang et al., 2004) outlined possible future change of snow based on the extraction of current trend and analysis of the relationship between snowfall and air temperature as well as precipitation. He suggested that the snow mass will slightly increase on the QTP and in Xinjiang and snow variability will fluctuate more strongly, implying an increase of snow disaster and spring drought. However, in northeast China and Inner Mongolia, snow mass is potential to decrease.

Different model simulation results show that snow melt runoff in the inland river basins of northwest China will definitely increase (Kang et al., 2002). Wang and Li (2006) chosen the upper Heihe River Basin as a case study area and used a degree-day factor based snowmelt runoff model to simulate the possible changes of snowmelt runoffs in response to a warming scenario of 4 °C air temperature rise. The simulation result indicate that a forward shifting of snow melting season, an increase in water flows in earlier melting season, and a decline in flows in later melting season would occur.

Table 4 Prediction of future glacier change in China

Glacier type	Current Area (km²)	2030			2050		
		Air temperature rise in summer (°C)	Reduced area (km²)	Decrease rate (%)	Air temperature rise in summer (°C)	Reduced area (km²)	Decrease rate (%)
Extreme continental type	22497	0.56	1237	5.5	1.40	3105	13.8
Sub-continental type	23649	0.46	3027	12.8	0.97	5770	24.4
Maritime type	13254	0.38	4095	30.9	0.65	6958	52.5
Total	59400	0.47	8359	14.1	1.00	15833	26.7

Permafrost

Due to the combined influence of climatic warming and increasing anthropogenic activities, substantial retreat of permafrost is expected on the QTP and in northeastern China during the 21st century. Different modeling approaches including empirical and more physically-based models were used to predict the permafrost change. Li and Cheng (1999) used the altitude model, an empirical model that related the lower limit of altitudinal permafrost with latitude (Cheng, 1984), to predict the permafrost existence. The results show that permafrost degradation is about 8 % when air temperature rises about 0.5 °C. When air temperature rises about 1.1 °C in 2050, the permafrost on the Plateau will change significantly with degraded area reaching about 18 %. More drastically, by the year of 2099, if the air temperature increases by an average of 2.9 °C on the Plateau, the degraded permafrost area will exceed 58 %. Almost all the permafrost in the southern Plateau and in the eastern Plateau will be in degradation (Li and Cheng, 1999; Li et al., 2003). However, it should be noticed that the response of permafrost in deep ground to climatic warming will be much lagged than that in the surface.

Nan (2005) also simulated future permafrost evolution on the QTP using a more physically-based model (Li et al., 1996). Simulation results show that in the case of 0.02 °C/yr air-temperature rise, permafrost area on the QTP will shrink about 8.8 % in the next 50 years, and high temperature permafrost with MAGT higher than –0.11 °C may turn into seasonal frozen soils. In the next 100 years, permafrost with MAGT higher than –0.5 °C will disappear and the permafrost area will shrink up to 13.4 %. In the case of 0.052 °C/yr air-temperature rise, permafrost area on the QTP will reduce about 13.5 % after 50 years. More remarkable degradation will take place after 100 years, and permafrost area will reduce about 46 %. Permafrost with MAGT higher than –2 °C will turn into seasonal frozen soils and even unfrozen soils.

Climatic warming will also have a great impact on the engineering properties of permafrost. Wu et al. (2000) predicted the permafrost stability along the QTH using the altitude model and a thermal stability based permafrost classification system (Cheng and Wang, 1982). According to the results, permafrost stability will change significantly under climatic warming. The area extent of permafrost along the highway will decrease and permafrost zone will move upward and be degrading. The areas of extreme stable zone, stable zone and sub-stable zone will decrease, while the areas of transit zone, unstable zone and extreme unstable zone will increase.

In northeast China, the south limit of permafrost would shift northwards upon a warming of 1.0~1.5 °C during the next 40~50 years. Present island permafrost would largely disappear, the south limit of permafrost would approach the present southern boundary of discontinuous permafrost zone with island taliks, which will be converted to island permafrost zone, and the continuous permafrost zone would been in the discontinuous permafrost zone with island taliks. At that time, the area of residual permafrost in the Da- and Xiao-Xing'anling Mountains would be 35 % of today's total permafrost area (Jin et al., 2006).

Summary

With the "roof of the world" occupied a large portion of land territory and as a very mountainous country, China's cryosphere area is vast. It is mainly composed of mountain glacier, high altitude permafrost, perennial and seasonal snow cover. Its distribution, change in the last few decades, and possible future change were overviewed in this paper.

According to the up-to-date statistics, there are 46,377 glaciers in China, covering an area of 59,425 km². The glacier ice reserve estimation is about 5600 km³ and the annual glacier runoff is about 61.6×10^9 m³. We summarized some recent investigations on the area change of glacier. It can be concluded that the glacier recession is generally significant in the marginal areas of the QTP and other mountains in west China but relatively small in the hinterland of the QTP. As a total, China's glaciers have shrunk 5.5 % since 1960s to date. The future recession of glacier would be very quick. Most of the glaciers with their area less than 1 km² would disappear before 2050. As a total, China's glacier area will decrease 26.7 % if air temperature rises 1 °C. However, it is predicted that the glacier runoff will increase and reach its maximum in 2030.

A new dataset of snow depth and SWE in China from 1978 to 2005 was established using the passive microwave remote sensing data. The statistics of snow cover area and snow mass are provided. The mean snow cover extent in China is about 8.9×10^6 km² and the steady snow cover extent is about 3.5×10^6 km². The maximum SWE is 95.9×10^9 m³. The annual snowfall recharge was estimated to be over 345×10^9 m³, but with great uncertainty. The variation of snow is fluctuated annually, with a slight increase trend. It seems this trend will be kept in west China before 2050 but in east China snow tends to decrease. The strong variability of snow would bring more snow related disasters. The snow melt runoff in northwest China is predicted to increase.

The permafrost area in China is about 1.72×10^6 km² and the seasonal frozen ground area is about 5.21×10^6 km². The ground ice reserve in permafrost might be huge. In the QTP, it is estimated as 10,923 km³. Significant permafrost degradation occurs in most permafrost regions in China. The permafrost on the QTP reduced about 0.1×10^6 km². The lower limit of permafrost elevated 25 to 80 m. Most of the island permafrost in northeast China has disappeared. Permafrost temperature is increasing and the increase speed is accelerating. Remarkable thickening at active layer of permafrost has been observed on the QTP and is even sharper in northeast China. The thinning of seasonal freezing depth is a commonplace in west China, supported by many evidences on the QTP and in Xinjiang. Model predictions show that permafrost will keep in degrading. One third to half of the permafrost on the Qinghai-Tibetan Plateau will be degraded. Most of the high-temperature permafrost will disappear. The permafrost in northeast China would retreat rather northward. The thermal stability of permafrost will be reduced, having a great impact to civil engineering in permafrost area.

It is also believed that the frangibility of environment in cryospheric regions of China will increase. Therefore, improving the understanding and predictability of cryosphere in order to alleviate the disadvantages caused by cryospheric change is very important.

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Role of snow and glaciers in hydrology and water resources: A Himalayan perspective

Pratap Singh

The major river systems of the Himalayas have large extent of snow and glacier covered area in their headwaters. These river systems receive substantial amount of melt water from the Himalayan glaciers into their annual flows and considered as the lifeline of the Indian sub-continent. Large quantities of water are released from the snow and glaciers during summer period when water from other sources is not much available and demand of water is very high. The water generated from seasonal snowmelt and glacier melt is considered a dependable source for irrigation, hydroelectric power generation and drinking water supply. During monsoon season, rainfall occurring in the lower and middle part of the basins adds to hydropower potential of these rivers. Glaciers are important not only as a source of water for different purposes but they also have a great influence on the climate. This review paper focuses on the melt rate, melt period and distribution of runoff from the Himalayan snow and glaciers and their role in the Indian water resources. Variability in flow regimes of the glaciers has also been discussed.

Introduction

Availability of freshwater is essential for human survival and for maintenance of ecosystem on land. More than half of humanity relies on the fresh water that accumulates in mountains. Growing populations, intensifying agriculture, increasing urbanization and industrialization have led to a fourfold increase in global freshwater abstractions since 1940. An effective management of mountain water resources, particularly discharges generated from the snow and glaciers, is essential to satisfy these growing demands. It is a key factor in development, particularly in Indian conditions with large areas under arid and semiarid conditions, where water availability is directly linked to food production for hundreds of millions.

Glaciers are very important source of fresh water and they act as a natural frozen reservoir that stores water during winters and release it in the summer. About 50 % of the glaciers located outside the polar region exist in high mountains of Asia and a large proportion of these glaciers drain into the landmass of the Indian sub-continent. The major river systems of our country, namely, the Indus, the Ganga, and the Brahmaputra originate from the Himalayas and have their headwaters extensively covered by snow during winters. These river systems receive substantial amount of melt water runoff is generated from the Himalayan snow and glaciers into their annual flows. During winters, all the glaciers are buried under seasonal snow. In the summer, first melting of accumulated seasonal snow takes place and then contribution from the glaciers starts.

Glaciers are considered to be very sensitive to the climatic conditions. They respond quickly to changes in the climatic environment, and their advancement or retreat can make small but damaging changes in sea level in decades. Retreat of glaciers and its impact on water resources is one of the current issues being debated since more than two decades. There are evidences that glaciers have retreated globally during last century. At present deglaciation is considered to be a world-wide problem including Himalayan region.

Himalayas and Himalayan Glaciers

The Himalayas, the youngest and fragile mountain system of the earth, have direct influence on climate control, regional hydrology and environment of the Indian sub-continent. The Himalayas are running in arcuate shape for about 2500 km between Indus and Brahmaputra with the width varying from about 200 to 400 km. These glaciers form a unique reservoir of fresh water supporting mighty perennial rivers such as the Indus, Ganga and Brahmaputra, which, in turn are the lifeline of millions of people. Orographically, this mountain range has been divided in three parallel longitudinal zones, namely, The Greater, the Lesser and the Outer Himalayas. An average elevation of greater Himalayan range is 6100 m and consists of continuous series of highly fossiliferous marine sedimentary rocks of different ages. The middle ranges (Lesser Himalayas) form intricate mountain system with an average height of 2600 – 4600 m and are predominately composed of crystalline and metamorphic rocks. The Outer Himalayas with an average elevation of 1000 to 1300 m are composed of sedimentary river deposits.

About 35 % of the geographical area in India is mountainous and 58 % of this is accounted for by the mighty Himalayas. The Indian Himalayan Region leis between 21°57' – 37°5' N latitudes and 72°40' – 97°25' E longitudes and covers an area of about 500,000 km² representing about 16.2 % of India's total geographical area. The region forms of snow-clad peaks and glaciers on higher Himalayas and dense forests in mid-Himalayas. The forest is the major land-use parameter, which covers above 52 % of the total reporting area of the region (Envis 2004).

Glaciation in the Himalayas is found to be more intense than the Alps and Rockies. Existence of snow and glacier fields in the Himalayas is mainly because of their ultra high altitudes, which compensates for such a large glaciation extent at low latitudes. The concentration of glaciers is higher in the western Himalayas than the eastern Himalayan region. Himalayas contain the largest number of glaciers in the world outside the Polar circles. The Himalayan glaciers have a large variation in their size.

Some of the largest glaciers are the Siachen Glacier (76 km), Hispar Glacier (62 km), Batura Glacier (58 km), and Baltoro Glacier (58 km) in Karakoram, Gangotri Glacier (30 km), and Milam Glacier (19 km) in Garhwal Himalayas, and Zemu Glacier (26 km) and Kanchanjungha Glacier (16 km) in

Table 1 Details of glacier inventory of some basins in the Himalayan region (Geological Survey of India 1999)

Basin	Sub-basin	Basin area (km²)	No. of glaciers	Glacierised area (km²)	Glacierised area (%)	Total ice volume (km³)
Jhelum	Shaliganga-Sookhnag	1516	5	1.8	0.12	0.02
	Sind	1142	57	39.9	3.50	1.40
	Vishav-Rembiara	1579	23	13.5	0.86	0.39
	Liddar	1283	48	38.9	3.04	1.49
Satluj	Baspa	1100	89	238.7	21.70	15.30
	Tirung	916	60	135.4	14.78	6.40
	Tagla-gyamthing	187	27	19.2	10.26	0.58
	Ropa	628	48	27.3	4.35	0.71
Bhagirathi	Bhilangna	1700	13	88.2	5.19	4.95
	Pilang	1335	23	48.5	3.63	2.96
	Jalandhri	694	64	104.9	15.13	4.65
	Jahnvi Ganga	1440	60	136.2	9.46	7.96
	Bhagirathi Ganga	1015	78	377.5	37.21	46.50
Tista	East Rathong	2351	36	58.4	2.49	3.02
	Talung	1271	61	142.9	11.25	8.65
	Changme Khangpu	1159	102	144.4	12.46	7.69
	Zemu	2392	250	359.9	15.05	20.25
Brahmaputra (Partially)	Manas	2194	4	1.5	0.07	0.02
	Kameng	12585	52	65.8	0.52	2.82
	Subansiri	8500	91	145.5	1.71	6.82
	Dibang	4725	14	10.7	0.23	0.30

Table 2 Snow and glacier melt contributions in some Himalayan rivers

River	Catchment area (km²)	Snow cover area (km²)		Snow and glacier contribution in the annual flows (%)
		Maximum	Minimum	
Ganga (up to Deoprayag)	19700	9080 (40.9 % of basin)	3800 (19.3 % of basin)	29 %
Chenab (up to Akhnoor)	22200	15590 (70.2 % of basin)	5400 (24.3 % of basin)	49 %
Satluj (up to Bhakra Dam, Indian Part)	22305	14498 (65.0 % of basin)	4528 (20.3 % of basin)	60 %
Beas (up to Pandoh Dam)	5278	2375 (45 % of basin)	780 (15 % of basin)	35 %

Sikkim Himalayas. In India, systematic studies of glaciers are about 30 years old. Some important glaciers like Gangotri Glacier, Gara Glacier, Shaune Garang Glacier, Gor-Garang Glacier, Kol Glacier, Neh-Nar Glacier, Bara Shigri Glacier, Chhota Shigri Glacier, Tipra Blacier, Dunagiri Glacier and Dokriani Glacier have been taken up for detailed studies on geomorphological, glaciological, sediment load, meteorological and hydrological aspects by various Institutions. Such studies were initiatiated by Geological Survey of India in mid 70s.

Since 1986 Department of Science and Technology (DST), Govt. of India also started Himalayan Glaciology Program and sponsored several research projects covering different aspects of glaciers in the Indian Himalayas. Keeping in view, the extent of snow and glaciers, and their importance in Indian water resources, much more data/information has to be collected and analyzed. Comprehensive studies would result in long-term data base establishment.

Inventory of Glaciers

In order to make inventory of Himalayan glaciers time to time efforts have been made by various investigators (Karpov & Kirmani 1968; Muller 1970; Vohra 1978, 1981). The quantum of work needs a lot of efforts and time to complete the inventory of the Himalayan glaciers on the desired level. Remote sensing based inventory of glaciers using IRS LISS-II and Landsat data are prepared (Kulkarni 1990, 1991). Glacier features, e.g. glacier boundary, ice divide, equilibrium line, ablation area, accumulation area and glacier lakes were mapped based on varying scales (1:50,000 to 1:250,000). Geological Survey of India (1999) has published first generation inventory of glaciers indicating about 4,038 glaciers in the Indian Himalayas, occupying approximately 35,760 km² of area. These numbers are being updated again and most recent inventory is expected to be published. Inventory of glaciers for few selected basins is shown in table 1. It is expected that during the last glacial cycle, the aggregate area occupied by the glaciers, in the Himalayas, must have been much larger and the glaciers must have extended to lower altitudes as compared to their position today.

Role of Snow and Glaciers in Indian Water Resources

Forecasting of the volume of water contained in the snowpack and release of water from snow and glaciers is needed for efficient management of water resources including flood forecasting, reservoir operation and design of hydraulic and hydrologic structures, etc. The summer and spring runoff, comprising mostly of snow melt and glacier melt is a source of water for irrigation, hydroelectric power production and drinking water supply. Melt water replenishes stock ponds, infiltrate the soils, and recharges groundwater supply. Heavy rainfall during the monsoon season adds to the richness of water resources. Some studies to estimate snow and glacier contribution into the annual flows of few Himalayan rivers have been carried out in India (Singh et al. 1997; Singh & Jain 2002; Kumar et al. 2007). Table 2 presents snow and glacier contributions into annual flows of Himalayan rivers area at the gauging sites in the foothills of the Himalayas along with maximum and minimum snow covered area.

It is clear that all these sites receive significant contribution from snow and glacier melt runoff into their stream flows. Hydrological investigation on runoff distribution and glacier hydrology has shown that maximum contribution from Himalayan glaciers is derived in the month of July and August. In general glacier melt period is considered from May – October (Haritashya et al. 2005; Singh et al. 2006).

In the Himalayan region, favourable geographical location and appropriate topographical setting provide excellent conditions for hydropower development. Melting of snow and glaciers ensures the continuous availability of streamflow which in combination of appropriate head because of the geological conditions in the mountainous areas provide a huge potential for hydropower generation. The potential of hydropower generation, in Himalayas, is not exploited to the extent that it could be. There is great scope to exploit the hydropower by commissioning micro-hydropower plants on a large scale on small glacier-melt streams. Hydrology is applied to design the hydropower plants safely to avoid flooding and minimize the consequent risk of failure, and to determine the water supply needed for cooling and safe disposition of wastes from thermal and nuclear energy plants. Hydro-power generation contributes about 26 % of total installed capacity of India. Details of hydro-power potential of important Himalayan rivers in India and its utilization, at present, is shown in table 3.

Table 3 Hydro-energy potential and utilization for important Himalayan rivers in India (Singh 1997)

River basin	Hydro-energy potential (MW) at 60 % load factor	Utilization in %
Indus	19,988	12.90
Ganga	19,715	17.07
Brahmaputra	34,920	1.06

Conclusions

In India, during summer period, substantial runoff is generated from the glaciers in all the Himalayan rivers. For few Himalayan rivers contribution has been estimated. Systematic studies are required for a better understanding of snow and glacier melt runoff processes and modelling. Such studies will improve management of available water resources in the region.

There is need for comprehensive studies to record the total volume and steramflow patterns from the different glaciers along with glacier retreat phenomenon in detail with focus on different factors affecting it. Possible impact of climate change on glacier retreat, and then on water resources of the region, will help the policy makers to adopt suitable strategies for the development of water resources, particularly in the high altitude areas.

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Changes in the extent of glaciers in the Russian Altay in the second half of the 20th century

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The paper investigates changes in the extent of glaciation in the Russian over the period of 1952–2003. The 1952 data are derived from the Catalogue of Glaciers of the USSR which in turn is based on the analysis of aerial photographs. The 2003 data are derived from high-resolution satellite imagery. During the assessment period, the number of glaciers has declined by 7.5%, the surface area of glaciers by 7%, and the glacier volume by 10%.

Introduction

This paper reviews the recent analyses of glacier change in the Altay Mountains, Russia focusing on the 1952–2003 period. This time period has been marked by an extensive data collection in the Altay including (i) mass balance observations accompanied by meteorological and hydrological observations; (ii) ground-based surveys of the extent of glaciers and positions of glacier termini; (iii) topographic maps, aerial photographs (obtained in 1952, 1961, 1975, and 1980) and satellite imagery (2003). In this paper, we summarise our recent findings on the changing extent of glaciers, reserves of glacier ice, and the number and morphological types of glaciers.

Changes in the extent of glaciers

Figure 1 presents rates of the retreat of termini of the largest glaciers of the Altay between the middle of the 19th century and the end of the 20th century. The general trend is that of a retreat, however, the irregular (3–5 between 1952 and 2003) observations of another 98 glaciers have shown that the rates of retreat vary significantly between individual glaciers and catchments. Usually, glaciers located on the same macroslope of a ridge behave in a similar way. For example, there is a strong correlation (correlation coefficient of 0.71) between the variations of terminus positions of Maly Aktru and Korumdu glaciers located on the northern macroslope of the North Chuya Ridge. However, even glaciers located in a very close proximity, e.g. Maly and Levy Aktru can exhibit an anti-phase behavior on a short time scale. The retreat rates varied in time too and even as recently as in 1987–1988 and 1993, amidst intensive degradation, some glaciers advanced in the central Altay albeit by a small rate of 2–7 m a^{-1} and in the subsequent years these gains were eliminated (Narozhny 2002, Narozhny and Nikitin 2003). On a longer time scale, a rapid glacier retreat from 1952–1961 was succeeded by a period of slow glacier wastage (up to 1980), followed in turn by accelerating melt, which was particularly strong between 1988 and 2003. The years of 1974, 1978, 1982, and 1998 were particularly unfavourable for the glaciers and climatic anomalies leading to intensive glacier melt were observed across the Altay in these years.

The rate of retreat depended on the size of glaciers. The largest glaciers (over 8 km² or over 5–6 km in length) were retreating faster and have lost more ice. By contrast, many very small (less than 0.5 km²) cirque and hanging glaciers remained stable. These differences necessitate assessments over the larger areas, i.e. different regions and mountain massifs within the Altay. Table 1 summarizes changes in area and volume of glacier ice for such areas quantified using aerial (1952) and Landsat imagery. Note that glacier parameters for 1952 have been obtained from the Catalogue of Glaciers (1978) which, in turn, was based on the 1952 aerial photos and not through

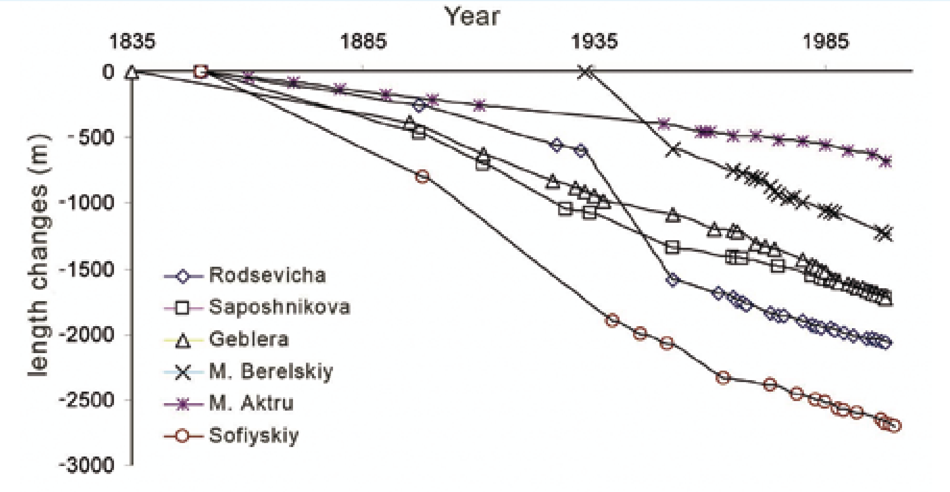

Figure 1
Cumulative changes in length (m) of selected glaciers in the Altay.

re-mapping of the original aerial photographs. Some changes have been made to the Catalogue of Glaciers statistics based on the later analysis of the 1952 data (Revyakin 1981, Mukhametov 1988, Narozhny et al. 2002).

Table 1 shows that in total, the Russian Altay has lost 56.7 km² of ice between 1952 and 2003. The lowest lost of ice (6–7 %) was observed in the Katun, North Chuya and South Chuya ridges which are located in the central Altay. These are the highest areas with absolute elevations exceeding 4000 m above mean sea level (a.s.l.) and 80 % of all glaciers of the Russian Altay is concentrated here. In the ridges located on the margins of the Altay (e.g. Kuray and Chikhachev), the deglaciation was more significant and surface area of the glaciers declined by 15–22 %.

Changes in the number of glaciers and their morphological type

With regard to different glacier types, the flat-summit glaciers have lost the largest proportion of their area (16 %) while the simple valley glaciers lost the lowest fraction (4 %). The total number of glaciers in the Altay has declined from 1030 to 953. This is a 7.5 % decline but in individual ridges it has been as high as 19 %. Glaciers that disappeared are mainly of cirque, hanging or niche type. Their size varied from 0.02 to

Table 1 Changes in area and volume of glacier ice in the Altay between 1952 and 2003. Note that small (less than 0.1 km²) glaciers have been included in this assessment. The Katun Ridge includes the Khoidun and Biruyksy glaciers

Ridge	Area, km²		Area reduction		Ice volume, km³		Ice volume reduction	
	1952	2003	km²	%	1952	2003	km³	%
Katun	319.05	298.24	20.81	6.5	15.476	13.641	1.835	11.8
South Chuya	216.01	202.41	13.6	6.3	12.055	11.086	0.969	8.0
North Chuya	166.04	154.66	11.38	6.9	9.695	8.885	0.81	8.3
South Altay and Karaalahinsky Mountains	57.0	51.9	5.1	8.9	3.064	2.740	0.324	10.6
Tabyn-Bogdo-Ala	31.1	28.2	2.9	9.3	1.703	1.441	0.262	15.4
Sailuygem and Chikhachev Ridges	6.3	5.33	0.97	15.4	0.245	0.211	0.034	14.0
Biya River Basin	9.4	7.27	2.13	22.6	0.327	0.268	0.059	18.0
Total for the Altay	**804.9**	**748.01**	**56.89**	**7.1**	**42.565**	**38.272**	**4.293**	**10.1**

0.1 km², and their length ranged between 50 and 200 m. Most of them were located below the long-term average of the equilibrium line altitude. The formation of new glaciers has occurred too due to the separation of the larger glaciers. Fragmentation of about 20 large glaciers has occurred and the most prominent example of this process is the fragmentation of the large flat-summit glaciers No. 252 and 253 in the Tabyn-Bogdo-Ola Ridge on the border between Russia, Mongolia and China. The aerial photographs of 1952, 1961, and 1975 show these glaciers as large glaciers with an area of 25.2 km². However, the satellite images of 2003 show that glacier No. 252 separated into four and No. 253 into six glaciers, respectively. The same process affected the compound valley glaciers too. For example, Bolshoy Aktru has separeted to form Levy and Parvy Aktru glaciers.

Changes in glacial volume

During the 1983 – 2003 and, in particular, 1996 – 2003 time periods, extensive surveys of glacier depth have been conducted in the central Altay by means of radio sounding. The techniques are discussed in Nikitin et al. (2000). Altogether, the depths of 120 glaciers of different type have been measured including 40 in the Katun, 41 in North Chuya, and 39 in the South Chuya ridges. The following relationships between glacier area and glacier volume have been obtained for glaciers of different types:

Valley glaciers:

$$V = 0.0444 A^{1,134} \quad (r = 0.94) \tag{1}$$

Cirque-valley glaciers:

$$V = 0.0464 A^{1,028} \quad (r = 0.89) \tag{2}$$

Cirque and cirque-hanging glaciers:

$$V = 0.0487 A^{1,244} \quad (r = 0.91) \tag{3}$$

where V is volume, A is area, and r is correlation coefficient between volume and area. These relationships have been obtained for the samples of 46 valley, 36 cirque-valley and 29 cirque and cirque-hanging glaciers. Equation (4) quantifies the link between volume and area of all these and another 9 flat-summit glaciers:

$$V = 0.0451 F^{1,128} \quad (r = 0.95) \tag{4}$$

The average depth of the surveyed glaciers was 51.5 m. The largest depth of 57.7 m occurred in the North Chuya Ridge; in the South Chuya Ridge it was 53.1 m and in the Katun Ridge the depth was the lowest at 47 m. The strong correlation between area and volume enables us to calculate ice reserves in the Altay as following: 13.6 km³ of ice in the Katun Ridge (338 glaciers); 11.1 km³ in the South Chuya (213 glaciers); 8.9 km³ in the North Chuya (181 glaciers). Ice reserves in the other ridges (Table 1) where another 97 glaciers with a total area of 92.87 km² or 12.5 % of the Altay total are located have been estimated as 4.7 km³. Thus in total, the Russian Altay at the end of the 20th century contained 38.3 km³ of ice or 34.5 km³ of water. Providing that the long-term average total glacial runoff in the Russian Altay is 1 km³, the estimated water reserves are equal to 35 years of glacier runoff. Note that Krenke (1982) estimated ice reserves of the Altay as 39 km³ and his estimation is included in Kotlyakov (1997). To estimate changes from 1952, equations 1 – 4 have been used assuming the stationary relationship between glacier area and volume. On this basis, the 1952 ice volume has been estimated as 42.565 km³, i.e. the ice volume has declined by 4.293 km³ (10 %) while reduction in glacier area was 56.89 km² (7 %) (Table 1). Thus, ice volume is declining faster than surface area. 80 % of the total ice reduction is contributed by glacier thinning and 20 % by reduction in area.

Conclusions

The glaciation in the Altay has been declining between 1952 and 2003: The number of glaciers has declined by 7.5 %, the area of glaciers by 7 % and their volume by 10 %. It is envisaged that the degradation of the Altai glaciation will continue and further fragmentation of glaciers will occur. Glaciers of complex morphological types will be replaced by smaller glaciers of simpler shape.

Acknowledgements
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Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions

Tobias Bolch, Sergei Marchenko

Trend analyses for the period from 1879 to 2000 at 16 climate stations located in and around Northern Tien Shan show an air temperature increase, which has become pronounced since the 1950s. This can be attributed mainly to a temperature rise in autumn and winter. However, the increase is less pronounced in the mountainous areas. For precipitation, there was a small increase on average, but no clear trend. Geothermal observations during 1974–1977 and 1990–2006 indicate that the permafrost has also been warming in the Tien Shan Mountains during the last 30 years. On average, the decrease was more than 32 ± 8 % in glacier extent and about 37.5 ± 9 % of glacier volume between 1955 and 1999 in the investigated six valleys. In 1999, active rockglaciers covered ca. 13 % of the glaciated area and contained roughly estimated an ice volume of about 3–4 % of the total glacier ice volume. The ice content of the whole permafrost area is probably much higher. Under continued warming, it can be assumed that glaciers will retreat and permafrost will degrade in Central Asia, the melting ground ice could increase future water supply, and the melt waters from permafrost could become an increasingly important source of fresh water in this region in the near future.

Introduction

High mountains have an important function as water storage and water supply for the surrounding regions. Its glaciers and ground ice are a major source of freshwater. This is especially true in arid or semi-arid areas, such as Central Asia. Therefore it is important to study their reaction to climate change.

The climate of the earth has always been characterized by natural variations. However, the mean annual air temperatures rose rather dramatically in the 20th century (IPCC 2001). This has caused increasing glacier retreat in many parts of the world (Haeberli & Beniston 1998). This trend intensified at the end of the last century and the areas of glacial ice coverage in Central Asia, like in other parts of the world, strongly diminished (Aizen et al. 2006; Bolch 2007; Khromova et al. 2003). Clearly, the permafrost also reacts to climate warming, e.g. in an acceleration of creeping of rockglaciers (Kääb et al. 2007) or a warming of the permafrost temperatures (Marchenko 1999, Vonder Mühll et al. 1998).

Nevertheless, climate, glacier and permafrost changes are not homogeneous worldwide.
For example, glaciers in the more continental Pamirs retreated less in the 20th century than glaciers in the more humid parts of Tien Shan (Hagg 2003; Liu & Han 1992).

The northern Tien Shan is an ideal area to study of these changes as the climatic conditions vary within short distances and there exists a comparatively dense network of climate stations in different altitudes as well as a permanent permafrost monitoring station. The studied mountain ranges, Zailyiskiy and Kungey Alatau, a main part of the Northern Tien Shan, are situated at the border between Kazakhstan and Kyrgyzstan (Figure 1).
These mountains, which rise up to an altitude of nearly 5000 m a.s.l., are characterised by a pronounced periglacial belt with the occurrence of many active rockglaciers (ice rich creeping mountain permafrost) between 3000 and 3600 m a.s.l. The average equilibrium line altitude of the glaciers is located between 3800 and 3900 m a.s.l.

Figure 1
Location of the study area; the investigated valleys are marked (arrows); locations of selected climate stations (1 Almaty, 2 Mynzhilki, 3 Tuyuksu, 4 Novorosijka, 5 Balykchi, 6 Kyrchin, 7 Karakol) and of the permafrost monitoring Station (P) are also indicated

Methods and Data

Climate

The analysis of climate change in northern Tien Shan is based on 16 time series of temperature and precipitation (Table 1), some of them long-term. Several of them are from stations at altitudes higher than 2000 m a.s.l. and four are even located above 3000 m a.s.l. As the quality of the series was not well known, they had to be tested for inhomogeneities. This was done visually by checking the graphs and by correlation analysis, based mainly on the time series of Almaty, which was homogenized by Böhner (1996). Inhomogeneities due to false values in the time series and location shifts of the stations were detected and corrected. However, gradually occurring bias, e.g. due to increased urbanization, could not be excluded. The purpose of the correlation analysis was also to determine, whether it is possible to transfer the data from stations with longer time series to the ones with shorter time series and to find characteristic stations for areas with homogeneous trends. In doing so, the study area was divided into four parts: the northern foothills with Almaty (848 m a.s.l.) as the representative station, the mountainous areas of Zailiyskiy Alatau (Mynzhilki, 3017 m a.s.l.), the deeply incised Chon-Kemin Valley (Novorosijka, 1524 m a.s.l.) and the Issyk-Kul basin (Karakol, 1740 m a.s.l.). In addition the Bolshaja Alma Atinsjkoje Ozero station was analysed due to its close proximity to the permafrost monitoring station.

Mapping and Estimation of the Ice Content of the Glaciers and Rockglaciers

The recent glacial ice coverage was mapped using a Landsat ETM+ scene from 8.8.1999. No snow covered the glacier tongues, but a few clouds occurred in the area of the glaciers, mainly at the southern slope of Kungey Alatau. A TM4/TM5 ratio image with a threshold of two was used to delineate the glaciers. Misclassified pixels of vegetated areas and lakes were eliminated using the Normalized Difference Vegetation Index (NDVI). A similar approach was successfully utilized for the Swiss Glacier Inventory (SGI) (Paul et al. 2002). Problems arose due to moraine cover on some glacier tongues caused by the similar spectral signal of the surrounding debris. With the help of a morphometric analyses and aerial images from the year 1990 the outline of glaciers with debris parts and bigger glaciers with cloud cover in the Landsat scene could be manually delineated. An evaluation shows that the accuracy is in the order of 3 % (Bolch & Kamp 2006).

In order to quantify the glacier change this data were compared to those of the soviet glacier inventory, which represents the situation in the study area of about 1955 (USSR 1966–1983). However, it has to be mentioned that the glacierized areas calculated from an existing map (scale 1:10 000) of Malaya Almatinka valley from the year 1958 (Simon et al. 1961) differ more than 5 % from the glacier areas (open parts) cited

Table 1 Characteristics of the climate stations incorporated into the analyses

Nr.	Name	Location	Altitude (m a.s.l.)	Time period
1	Almaty (Alma-Ata)	Foothills	848	1879 – 2000
2	Ust-Gorelnik	Zailiyskiy Alatau	1943	1938 – 1991
3	Verchnij-Gorelnik	Zailiyskiy Alatau	2272	1970 – 1989
4	Mynzhilki	Zailiyskiy Alatau	3017	1937 – 1996
5	Tuyuksu	Zailiyskiy Alatau	3434	1972 – 1996
6	Bol. Alma Ozero	Zailiyskiy Alatau	2450	1932 – 1996
7	Assy	Zailiyskiy Alatau	2218	1952 – 1966, 1981 – 1990
8	Novorosijka	Chon-Kemin	1524	1931 – 2000
9	Kyrchin	Kungey-Alatau	2305	1980 – 1999
10	Balykchi (Rybache)	Issyk-Kul Basin	1670	1931 – 2000
11	Cholpon-Ata	Issyk-Kul Basin	1645	1929 – 2000
12	Krasnij Oktjabr	Issyk-Kul Basin	1645	1946 – 1998
13	Karakol (Prshevalsk)	Issyk-Kul Basin	1744	1879 – 1996
14	Pokrovka	Issyk-Kul Basin	1740	1951 – 2000
15	Karabatkak-Glacier	Terskey Alatau	3415	1956 – 1999
16	Tien Shan	Ak-Shiyrak	3614	1930 – 1996

Data sources: Böhner (2004), Giese (2004), published in Giese & Moβig (2004), Institute for Geography Almaty und Institute for Hydrometeorology Bishkek.

in the Soviet Glacier Inventory of this region (Vilesov & Khonin 1967). Therefore the probable maximum errors of the presented numbers of glacier retreat is about 8 %.

The outlines of the rockglaciers were drawn manually based on the mentioned Landsat scenes and aerial images as well as field investigations. The latter were also conducted to estimate the thickness of the rockglaciers.

More than 150 glaciers and more than 60 rockglaciers in six selected valleys were studied in detail using GIS and DEMs derived from SRTM, ASTER data and topographic maps. The selected valleys represent the different climatic conditions of Zailyiskiy and Kungey Alatau and were accessible by foot to obtain ground-based measurements. Unfortunately, the southern slope of Kungey Alatau could not be included in this study due to massive cloud cover in the available Landsat-ETM and ASTER scenes.

The estimation of the ice content is based on the following assumptions in table 2.

Table 2 Assumptions for estimating rockglacier and glacier ice content

Estimation of Glacier Thickness[1] [m]:	28.5 (a [km^2])$^{0.357}$
Estimation of Rockglacier Ice Content[2]	40 – 60 % by Volume
Estimation of average permafrost thickness in Rockglacier[3]	20 m

Based upon: 1 Chen & Ohmura (1990), 2 Arenson et al. (2002), Barsch (1996), Gorbunov & Severskiy, 3 Croce & Milana (2002), Gorbunov & Titkov (1989), own investigations

Permafrost – temperatures, distribution and ice content

The initial investigations of mountain permafrost in the Tien Shan began in the mid-1950s (Gorbunov 1967, 1970). General features of permafrost distribution in the Tien Shan Mountains are resulting from latitudinal and altitudinal zonality, and from changes in climatic and topographic factors. The regional patterns of permafrost distribution depend on elevation, slope, and aspect, which have a major influence on incoming short-wave radiation to the ground surface. Vegetation and snow cover, ground texture and moisture content, winter air temperature inversion, surface and groundwater presence and movement, and climatic and geothermal conditions are also among the most important parameters shaping the mountain permafrost distribution.

Coarse blocky debris of various origins is widespread in the Tien Shan and occupies a large area of high-mountain territory. Convective mass and heat transfer, especially during the cold period, are very typical for the blocky material because of its high porosity. The measurements in the Zailiysky Alatau Range during 1974–87 show that the temperatures inside the coarse debris are typically 2.5–4.0 °C colder than the mean annual air temperature (MAAT) (Gorbunov et al. 2004). For this reason the altitudinal distribution of rockglaciers are a few hundreds meters lower than that of open glaciers.

In mapping of mountain permafrost distribution in Tien Shan, the traditional approach has been based on the dividing of mountain ranges into sub-belts of different types of permafrost distribution (Gorbunov 1986). Within the overall permafrost belt in the Northern Tien Shan, sub-belts of sporadic (2700–3200 m a.s.l.), discontinuous (3200–3500 m a.s.l.), and continuous (3500 m a.s.l. and higher) permafrost have been identified (Gorbunov 1986; Gorbunov et al. 1996). The total area of permafrost within each of these sub-belts is: sporadic – not more than 30 %, discontinuous – not more than 70 %, continuous – not less than 90 %. However, small isolated patches of permafrost can be found much lower than 2700 m a.s.l. These patches occur at the feet of north-facing or shaded slopes inside the coarse blocky debris or beneath a mossy cover even at 1800 m a.s.l. where the MAAT is 3.0–4.0 °C (Gorbunov 1993).

An alternative approach for the mapping of mountain permafrost is the modeling of ground temperature and permafrost distribution using process-based models (Marchenko 2001, 2006). Such an approach allows for a spatial and temporal extrapolation of the permafrost thermal state and distribution and is also well suited for studies of the permafrost response to climate change. But process-based models require an extensive set of input data such as meteorological data, surface characteristics (vegetation, snow cover), ground thermal properties, and topography.

For the modeling of altitudinal permafrost within rugged topography, the basic data set is a digital elevation model (DEM). The grid-based map of meteorological variables could be used as input data.

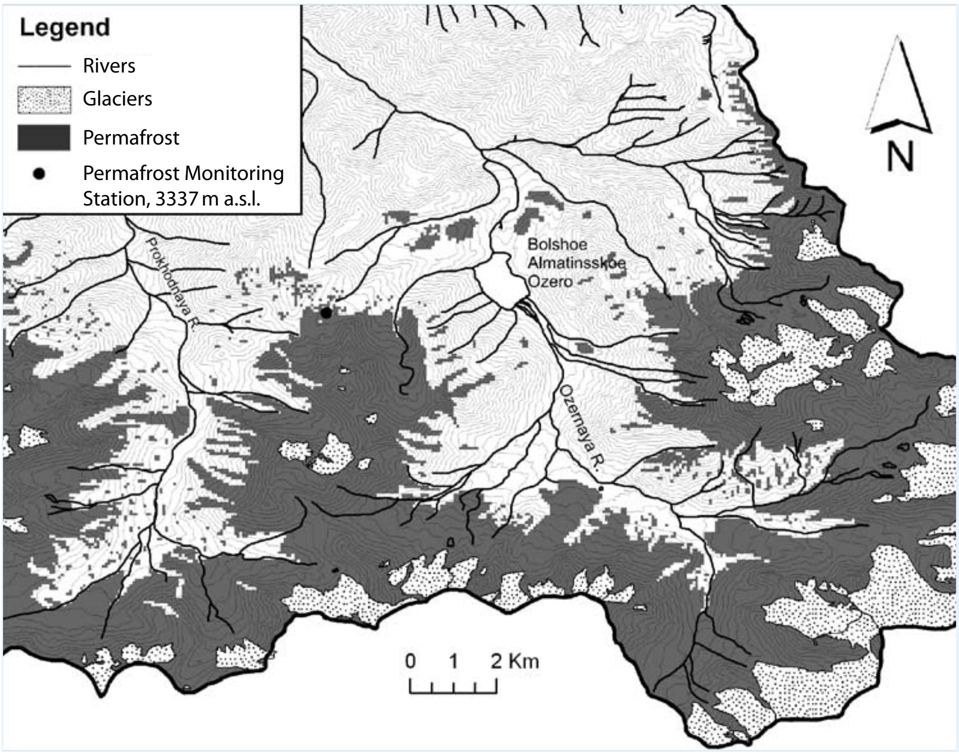

Figure 2
Fragment of the modeled map of permafrost distribution within the Bolshaya Almatinka River basin.

The investigated area was overlaid with a grid (250 × 250 m). The calculation of the ground temperature regime for each grid point was accomplished with an external program module, which can be called from the GIS. One result of the calculation is a database file containing the ground temperatures for each grid point. Because the goal of the calculations was to assess the permafrost extent, the mean annual ground temperature (MAGT) at 20 meters depth was selected as an output. This information was transferred back into the GIS using interpolation methods and producing a grid with a cell size of 100 × 100 m (Figure 2).

The mean annual temperature at the permafrost table and the heat flux at the bottom are the main thermal characteristics of permafrost. These parameters are very important not only for estimating the distribution and thickness of permafrost, but also for the evaluation of the sensitivity of permafrost to climate change and to natural or human-induced disturbances. The first systematic permafrost temperature measurements in the Northern Tien Shan began in 1973 (Gorbunov & Nemov 1978). One of the permafrost research stations of the Russian Academy of Sciences was established at 2500 m a.s.l. in 1974. The area of original permafrost studies in the Northern Tien Shan is located within the Bolshaya Almatinka river basin within the altitude range between 2000 and 3500 m a.s.l. During the last 30 years, staff members of the Kazakh Alpine Permafrost Laboratory, which belongs to the Yakutsk Permafrost Institute, conducted permafrost investigations. A variety of methods, including measurements of permafrost temperature, the active layer thermal regime and thickness, spring water temperatures, and DC resistivity soundings were used (Gorbunov & Nemov 1978; Zeng et al. 1993; Gorbunov et al. 1996).

There are 21 active thermometric boreholes with depths ranging from 2.2 m to 300 m in different landscape settings and at varying altitudes (2500 – 3330 m a.s.l) available for measurements in this region near the two permafrost stations in the Zailiysky Alatau. Ground temperature measurements are carried out by using thermistor sensors (MMT-4 and TSM-50) with a sensitivity 0.02 °C and an accuracy of not less than 0.05 °C. There are five sites equipped with temperature data loggers (StowAway Onset Computer Corporation) that have been in operation since 1997. These sites were established as a contribution to the IPA Circumpolar Arctic Layer Monitoring (CALM) project. Data from these sites are regularly added to the CALM site database. A few deep boreholes in the Northern Tien Shan belong to the Global Terrestrial Network of Permafrost (GTNet-P) Program (Burgess et al. 2001).

Initial geothermal observations (1974 – 1977) in boreholes in the northern Tien Shan showed that the permafrost temperatures within the loose deposits and bedrock at the altitude of 3300 m a.s.l vary from –0.3 °C to –0.8 °C (Gorbunov & Nemov 1978). Thickness of permafrost in this area varied from 15 to 90 m and the maximum active layer thickness reached 3.5 – 4.0 m.

Mountain permafrost and associated periglacial landforms contain large quantities of stored fresh water in the form of ice. The lacustrine and sometimes alluvial sediments, moraines, rockglaciers and other coarse blocky material have especially high ice content (20 – 80 % by volume). During the deep excavations (down to 12 m) in the in the Late Pleistocene and Holocene moraines, near one of the permafrost research stations (3336 m a.s.l), massive, syngenetic cryogenic formations with 15 – 20 cm thick ice lenses were revealed at depths below 4.0 – 4.5 m. The measured excess ice content in these formations amounts to 10 % to 40 % by volume (Gorbunov & Nemov 1978). These cryogenic formations can be treated as proof that permafrost has continuously been in existence here during the entire postglacial time.

According to Gorbunov & Severskiy (1998) the total volume of ground ice in the Northern Tien Shan is about 56 km³ which equals 62 % of the surface ice volume for the same territory. The estimated ground ice volume for the Bolshaya Almatinka river basin is about 0.6 km³ or 87 % of the surface ice volume in the basin (Gorbunov & Severskiy 1998). It should be noted that this assessment was performed for the whole permafrost area in the region. Frozen ground within the permafrost area was classified as bedrock (1 % ice content), coarse debris filled with fine-grained soils (ice content 20 %), and coarse debris unfilled with fine-grained soils (ice content 50 %). This approximate evaluation shows that the quantity of water stored as a ground ice in the Tien Shan is comparable to the volume of modern glaciers in the same region.

Recent Climate Changes

All trend coefficients of MAAT for the time period from 1950 to 1996 (Table 3) are positive. Almaty and Karakol, two stations not situated in the high mountain area, have higher positive trends than the high mountain stations, Mynzhilki and Tien Shan, and the valley station Novorosijka. Analyzing all available stations, it could be stated that there is a decreasing trend with altitude, but the trend is still positive in the high altitudes of Zailiyskiy and Kungey Alatau. Giese & Moßig (2004) even found a negative trend in high altitudes for Central Asia.

A more detailed analysis of the temperature development showed that the increase in the MAAT was, for the majority of the high mountain mountain stations above 2000 m a.s.l., caused by the strong rise of the temperatures in autumn, whereas the temperature increases of the summer half-year were less pronounced (Table 3). In contrast, the summer temperature rise at the Tien Shan station, situated in central part of Tien Shan was more pronounced than the autumn and winter air temperature rise.

Table 3 Trend coefficients for the yearly and seasonally air temperature change of the time period 1950 – 1996

Station	Alt. [m a.s.l.]	Trend coefficients [K/100a]				
		Year	MAM	JJA	SON	DJF
Almaty	848	2.37	+1.12	+0.68	+**2.53**	+2.03
Atinsk. Oz.	2516	0.57	−1.25	+1.03	**+1.86**	-0.23
Mynzhilki	3017	2.04	+1.97	+3.22	**+3.54**	+1.63
Novorosijka	1524	1.16	−0.16	+1.16	**+3.49**	+2.29
Karakol	1718	2.66	+1.6	+2.65	**+3.25**	+3,34
Tien Shan	3614	0.8	−0,26	**+1,54**	+1,27	+0.23

Two facts should be mentioned regarding the air temperature trends (Figure 3). First, the stations at the foothills are located mostly in the area of larger settlements and therefore, the higher air temperature increase could certainly be at least in part due to an increased urbanization of the surroundings. Second, the choice of the beginning and end times for the calculation of the air temperature trend coefficients has a considerable influence on the value. For this study, they were chosen on the basis of the availability of the data, and in such a way that the trends are clearly visible but not unrealistically exaggerated.

It is well known that the variation in precipitation is spatially and temporally much higher than the variation in temperature. A homogeneous trend in precipitation, as was obtained for temperatures, could not be detected. Since the 1950s at the latest, precipitation has risen slightly at the stations below 2000 m a.s.l., whereas it has decreased at the high mountain stations since the middle of the 1960s. The trends were similar in summer and winter. In recent times these trends seemed to reverse; thus it cannot be stated that there is a general change in precipitation conditions.

Glaciers and Glacier Changes Since 1955

In the six investigated valleys, three glaciers advanced, seven had more or less the same size while a particularly strong area loss could be measured from about 1955 until 1999 at all the other glaciers. The glacier extent diminished, on average, by about 32.6 ± 8 % in area (from ~247 to ~164 km²).

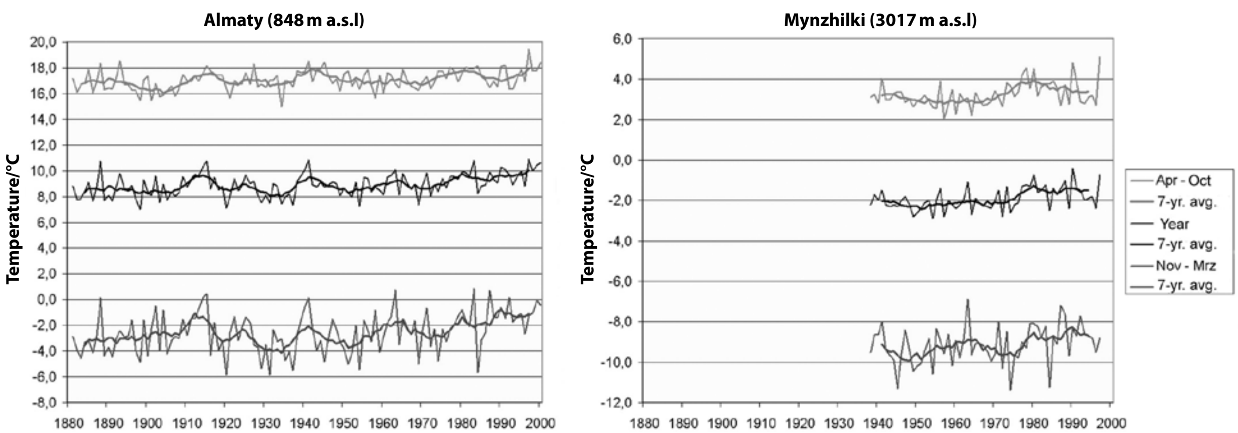

Figure 3 *Time Series of yearly air temperature and the temperatures of the summer-and the winter half year for the stations Almaty and Mynzhilky located in Zailiyskiy Alatau (Nr. 1 and 2 in Figure 1).*

The estimated volume of glaciers diminished from ~10.7 to ~6.7 km³ (~37.5 ± 9 %). However, the individual glacier retreat varied strongly (from –16 % to –38 % in area) depending on size, location, and climate conditions. In general, larger glaciers react more slowly to a modification of the climate and glaciers in more maritime climates are retreating more than those located in more continental climates. However, radiation and precipitation also clearly have a high impact (Bolch 2006, 2007). These results are similar to those obtained by Vilesov & Uvarov (2001), who found a change of 29.2 % in glacier area and 32.2 % in glacier volume on the northern slopes of Zailiyskiy Alatau from 1955 to 1990.Analyzing the time periods 1955 – 1979, 1979 – 1990 and 1990 – 1999 shows that the retreat rate was highest between 1979 and 1990 (Bolch 2006, Table 4). The glacier recession in the high continental areas of Tien Shan, such as the Terskej Alatau or the Ak-Shirak range in Inner Tien Shan is less pronounced (Aizen et al. 2006; Narama et al. 2006).

Rockglaciers and Permafrost

Rockglaciers are the clearly visible form of mountain permafrost and they are widespread in Northern Tien Shan. Figure 4 shows the occurrence of these creeping permafrost bodies as well as the glaciers in three investigates valleys at the northern slope of Zailyiskiy Alatau.

More than 60 active rockglaciers cover an area of about 21.4 km² (ca. 13 % of the glaciated area) in the investigated valleys. However, the occurrence of the rockglaciers is variable in the study area. The rockglacier coverage varies from less than 1 % of the area above 3000 m a.s.l. in Turgen valley to nearly 5 % in the Bolshaja Almatinka valley (Table 5). Detailed investigations of the rockglacier density can be found also in Gorbunov & Titkov (1989) and Kokarev et al. (1997).

The active rockglaciers contain, roughly estimated, an ice volume of more than 0.2 km³, which is on average more than 3 – 4 % of the glacier volume. Whereas the ice volume of the rockglaciers in Turgen valley is only about 1.5 %, it approximates 10 % in Bolshaja Almatinka valley, where most of the water supply for the million city Almaty originates from (Table 6).

The water storage of the rockglaciers compared to the glaciers in Northern Tien Shan is about two to three times higher than in the Alps, where it was estimated to be 1,2 to 1,5 % (Barsch 1977), but lower than in the Central Andes of Chile, where the water storage was estimated to be bigger than 10 % (Brenning 2005).

Recent studies show an acceleration of rockglacier movement throughout the Alps, which is probably mainly caused by the temperature rise (Kääb et al. 2007).

Table 4 Area changes of the glaciers in the investigated valleys for different time periods; based on Bolch (2006), Cherkassov et al. (2002), USSR Akademia Nauk (1966 – 1983) and Soviet topographic maps. The probable error of the numbers is about 8 %

Investigated Valley	Area change 1955 – 1999		Area change 1955 – 1979		Area change 1979 – 1990		Area change 1990 – 1999	
	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]
Malaya Almatinka	–37.6	–0.85	–13.2	–0.69	–22.8	–1.42	–6.9	–0.77
Bolsh-Almatinka	–34.5	–0.78	–17.5	–0.92	–15.9	–0.99	–5.7	–0.63
Levyj Talgar	–33.6	–0.76	–15.1	–0.76	–20.8	–1.30	–1.2	–0.14
Turgen	–36.5	–0.83	–17.4	–0.92	–15.0	–0.94	–9.5	–1.06
Average	**–34.5**	**–0.78**	**–16.5**	**–0.69**	**–18.0**	**–1.64**	**–4.5**	**–0.48**
	Area change 1955 – 1999		**Area change 1955 – 1979**		**Area change 1979 – 1999**			
	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]		
Chon Aksu	-38.2	-0.87	-29.9	-1.25	-11.8	-0.59		
Upper Chon Kemin	-16.4	-0.37	-9.3	-0.46	-7.8	-0.32		
Average all	**32.6**	**-0.74**	**-18.5**	**-0.77**	**-17.3**	**-0.86**		

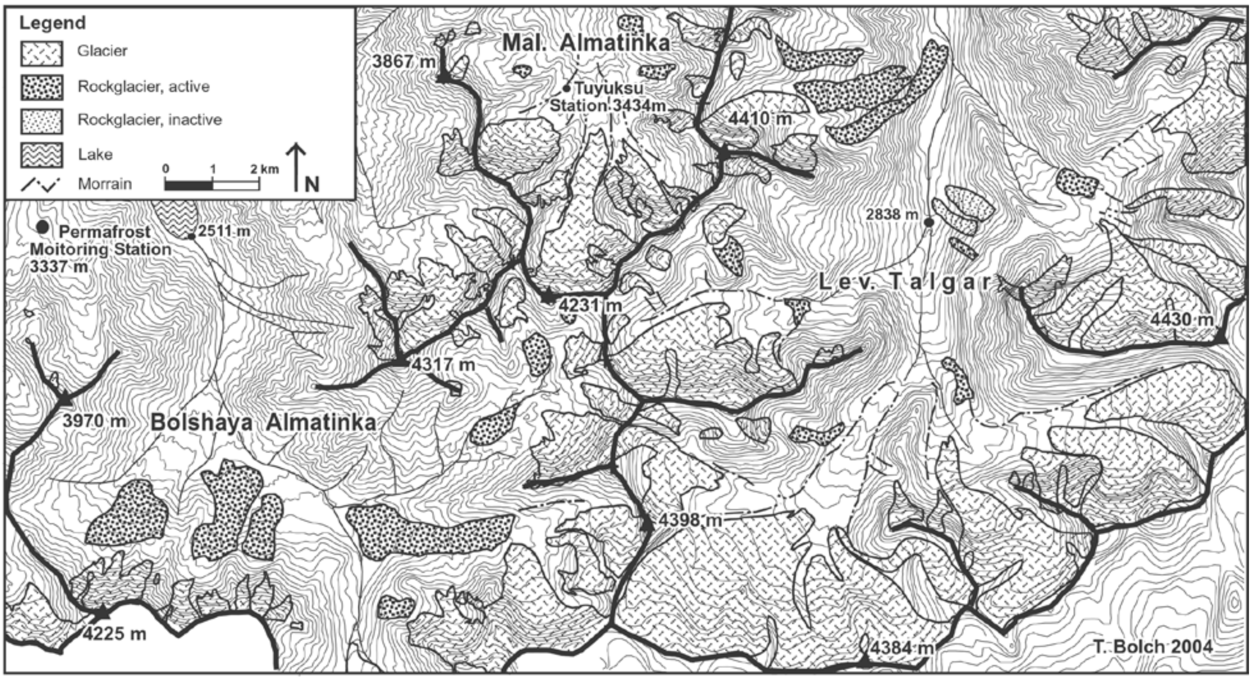

Figure 4 *Location of the permafrost monitoring station and the Tuyuksu glacier station as well as locations of the glaciers and rockglaciers in the valleys Bolshaya, Malaya Almatinka, and Levyj Talgar.*

Table 5 Comparison of the area of glaciers and rockglaciers

Investigated Valley	Area of Glaciers	Portion of Study Area > 3000 m a.s.l.	Area of active Rockglaciers	Portion of Study Area > 3000 m a.s.l.	Rockglaciers/ Glaciers
Bolshaja Almatinka	16.45 km^2	16.3 %	4.77 km^2	4.7 %	0.29
Malaja Almatinka	5.79 km^2	15.4 %	0.47 km^2	1.2 %	0.09
Levij Talgar	48.35 km^2	29.4 %	5.58 km^2	3.4 %	0.12
Turgen	22.98 km^2	13.5 %	1.16 km^2	0.7 %	0.05
Chon-Aksu	38.62 km^2	16.3 %	6.22 km^2	2.6 %	0.16
Upper Chon-Kemin	32.2 km^2	15.4 %	3.2 km^2	3.2 %	0.10
Sum or Average	164.39 km^2	20.0 %	21.4 km^2	2.65 %	0.13

Table 6 Estimated ice volume of the glaciers and rockglaciers

Investigated Valley	Glacier Ice Volume	Rockglacier Ice Volume	Rockglacier/ Glacier Ice
Bolshaya Almatinka	0.51 km^2	0.048 km^2	9.4 %
Malaya Almatinka	0.18 km^2	0.005 km^2	2.6 %
Levij Talgar	2.23 km^2	0.056 km^2	2.5 %
Turgen	0.88 km^2	0.012 km^2	1.3 %
Chon-Aksu	1.48 km^2	0.062 km^2	4.2 %
Upper Chon-Kemin	1.39 km^2	0.032 km^2	2.3 %
Sum or Average	6.67 km^2	0.214 km^2	3.2 %

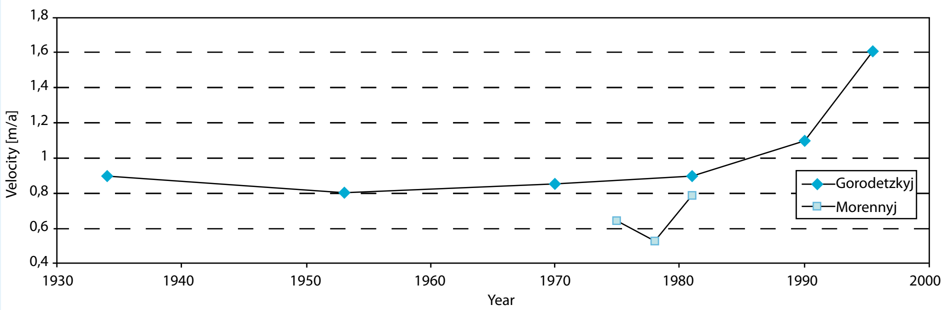

Figure 5
Rate of movement of the frontal lobe of the rockglaciers Gorodetzkij and Morennij; based on Gorbunov et al. *(1992) and Marchenko (2003).*

Measurements of the movement of the rockglaciers in Northern Tien Shan also showed a tendency to speed up (Gorbunov & Titkov 1989; Gorbunov et al. 1992). A long time series of front variation measurements exists for the rockglacier Gorodetzkij (1923–2003, Marchenko 2003). An analysis of this time series also showed an acceleration of the rockglacier movement (Figure 5).

Geothermal observations during 1974–1977 and 1990–2005 indicate that permafrost has been warming in the Tien Shan Mountains during the last 30 years. The increase in permafrost temperatures in the northern Tien Shan during 1974–2005 varies from 0.3 °C to 0.6 °C . In accordance with interpolation of borehole temperature data, the active-layer thickness (the layer of ground subject to annual thawing and freezing in areas underlain by permafrost) showed an increase during the last 30 years from 3.2–3.4 m in the 1970s to a maximum of 5.2 m in 1992 and to 5.0 m in 2001 and 2004 (Figure 6). The average active layer thickness for all measured sites increased by 23 % in comparison to the early 1970s.

As a result of a deep ground thawing, a residual thaw layer (talik) between 5 and 8 m in depth has appeared at several sites (Figure 6, b).

Modeling of the permafrost thermal state (Marchenko et al. 2007) indicates significant changes in permafrost temperature and extent during the 20th century in the Tien Shan Mountains. The main objectives of the modeling process were to estimate the permafrost thermal regime and to assess the area where permafrost has disappeared during the second part of the nineteenth century.

The results of numerical simulations show that the permafrost area within the altitudinal range of 2500–2700 m a.s.l. was about 20 % larger during the middle of the Nineteenth century compared to the present. Near the lower altitudinal boundary of perma-frost distribution the permafrost temperatures now are close to 0 °C and at some sites permafrost degradation has already started. Analysis of measured active layer and permafrost temperatures coupled with numerical thermal modeling (permafrost temperature reanalysis) shows that most of the recently thawed permafrost was formed during the Little Ice Age. The modeling of alpine permafrost dynamics shows that the altitudinal lower boundary of permafrost distribution has shifted upward by about 150 m since the end of the Little Ice Age (circa 1850). During the same period, the area of permafrost distribution within the Northern Tien Shan decreased by approximately 16 % (Marchenko et al. 2007).

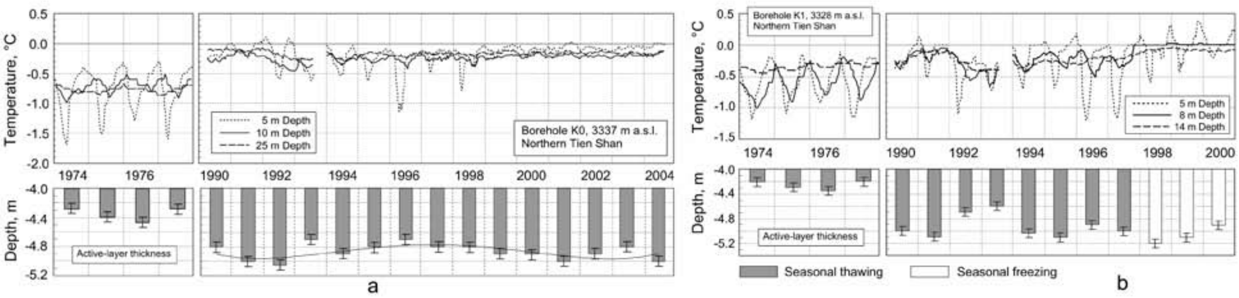

Figure 6 *Permafrost temperatures and active-layer thickness variations during 1974–1977 and 1990–2004 measured in two boreholes at the permafrost monitoring station (the location of this observatory is shown in figs. 1 and 2).*

Discussion and Conlusion

Glaciers are, in comparison to permafrost, more sensitive components of the cryosphere, reacting rapidly to climate changes. This reaction is reflected in the shrinkage of the glaciated area, the decrease of glacier volume and an increase of glacier runoff. Due to possible continued warming, glaciers will probably retreat to the highest elevation, lose some of their volume, and some of them will disappear completely and will contribute much less melt water to a river runoff. Permafrost, as a more conservative component of the cryosphere, could remain in a relatively more stable state than glaciers. While the increase in permafrost temperature may change many of its physical properties, a major shift will occur when permafrost starts to thaw from its top down. The most significant impacts on permafrost thermal state will be observed near the lower boundary of the alpine permafrost distribution; the region where the frozen ground is very sensitive to changes in surface energy balance.

Thawing and degradation of ice-rich permafrost could provide additional amounts of melt water to river runoff. In the high-mountain regions, the further near-surface permafrost degradation will probably be accompanied by a transformation in environmental conditions and may lead to slope instability and permafrost-related hazards such as landslides, thermokarst, and mudflows.

Our estimation of ground ice volume in the Northern Tien Shan Mountains was limited to rockglaciers and did not take other forms of ground ice within the permafrost area into consideration, similar to the estimation described by Gorbunov & Seversky (1998). It is possible that our rough assessment of rockglacier ice content somewhat underestimates the real values. No special investigations of the internal structure of rockglaciers and its ice content were carried out in the Northern Tien Shan so far. Our recent investigations demonstrated the presence of a significant amount of layered ice in the frontal part of rockglaciers. Several sections of buried ice with a total thickness up to 8 – 10 m were found in the front scarps of rockglaciers at an elevation of 3100 m a.s.l. Crystal structure and bubble shapes in the ice are similar to those found in glacier ice. These findings allow us the rough estimation of some morphologic type (near ice) of rockglaciers with ice contents of up to 80 % of the entire volume of these cryogenic landforms.

Future research focusing on the estimation of the contribution of permafrost and ground ice depletion to river runoff will make it possible to define the proportion of each runoff component (liquid/solid precipitation, glaciers and permafrost) in the total river runoff more precisely. In order to make these estimates, we need to seek explanations of the physical processes and mechanisms controlling these phenomena.
The assessment of ground ice volume and its role in freshwater runoff will allow the establishment of a predictive estimation of river runoff in accordance with regional scenarios of climate change in the Tien Shan.

Established relationships between recent climate change, glaciers retreat, permafrost warming and degradation, and changes in surface water runoff in the high-altitude Central Asia region will make it possible to predict the potential volume of ground ice that could be involved in the actual contribution to fresh water runoff. When coupled with obtained hydrologic data, a spatially distributed thermal model (Marchenko 2001) will provide essentially new information on the impact of climate warming on regional hydrology. This knowledge will facilitate climate change detection, climate impact assessments, planning for adaptation to climate and its extremes and will, in addition, support many socio-economic and environmental applications especially in fields such as land use planning and water resources management.

It can be assumed that under continued warming, the glaciers of Central Asia will retreat and the permafrost will degrade. Water from the melted ground ice could increase future water supply, and the melt waters from permafrost regions could become an increasingly important source of fresh water in this region in the near future. This is especially true for the summer months, when the need for water is highest due to irrigation.

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Ground ice and icings of Central Asia: geography and dynamics

A. P. Gorbunov

The perennial ground ice and the icefields in the Tien Shan and Pamir Alai mountains are considered in this study. Some data on the seasonal snow and ice of the pereletok Kazakh hammocky topography Saryarka is also introduced. Perennial ground ice is confined to the permafrost belt of high mountains. The zone with the biggest ice fraction belongs to Holocene and sometimes Late Pleistocene moraines, rock glaciers, macro fragmental scree slopes and lacustrine deposits. Often, the volume of ice in these deposits reaches 50 %. They contain mainly buried, segregated, injection, infiltration, ice cement and sublimation ice. However, the principal mass of ground ice is confined to the rock permafrost zone. Vein massive ice of different origins represents the present foundation. Its average content in the rock is estimated at 1 %. Yet, extensive ice deposits in rock permafrost zones are the predominant form of ice existence, amongst other lithogenous structures, in the highlands. The Central Asian mountains contain ice of almost all genetic phases. Only buried sea ice clusters and polygonal ice wedges have not been identified yet. According to a preliminary assessment, the total volume of ground ice in the region is not less than 500 km³. Special attention must be paid to seasonal ice and ice of pereletok of Saryarka. The ice volume of the largest lenses is about 5–6 m³. There is also some information about seasonally massive ice beds. It should be mentioned that ice of pereletok was a frequent occurrence in the first part of last century, but can no longer be considered typical at the present time. The perennial ice of the highlands is comparatively stable and only reacts slowly to global warming, distinguishing it from glaciers. Therefore, the relation of surface to ground ice is changing in favor of the latter one. The relation has changed in some regions from 50 to 90 % over the last 50 years. In other words, the glacier ice volume is almost equal to the ground ice volume. There are some areas where glaciers have disappeared during the Holocene, while ground ice was preserved. Large icings are confined to the permafrost zone. The largest of them can amount to several km² in area. The conditions for their creation have degenerated during the recent decades compared to the end of 19th and beginning of the 20th century. During that period some of the ice deposits lasted throughout the year.

Introduction

The area considered in the present studies includes the following mountain ranges: Saur-Tarbagatai, Semistai, Urkashar, Barlyk, Maylitau, Dzhangar (Jetysu) Alatau, Tien Shan, including its Eastern (Chinese) part, Gissar-Alai, Pamir including its eastern margin located in China. The permafrost zone in these mountains is limited in the West by the Sukhaktau range (67°30´), in the East by the Karlyktag range (93° E), in the South by Ishkashim, and the Pamir range (37° N), and in the North by the Saur -Tarbagatai range (47° N). The permafrost zone in the mountains of the northern part of this region is located mainly at elevations higher than 2200 m a.s.l., in the far southern parts above 3800 m, in the western parts (38° 20´ N) above 3600 m, and in the eastern parts (43 °N) above 2800 m. The total area containing permafrost is approximately assessed at 272,000 km² (Gorbunov et al. 1996). The highest mountain ranges in the region are currently subjected to glaciation. The total area of all glaciers was assessed at 27,000 km² about 50 years ago (Vilesov et al. 1989; Dolgushisn et al. 1989). At the present time, the total glacier area is decreasing annually (Vilesov et al. 2002). According to the most conservative estimates it is now less than 25,000 km².

Permafrost is also located in mountains that presently have no glaciers such as the Tarbagatai and Manrak, the territory between the Saur Tarbagatai and the Dzhungar Alatau, the Barlyk and Urkashar in the Dzhangar Alatau, the Tastau and Koyndytau ranges in the territory of China, the western part of the Borokhoro range in the Tien Shan, as well as the Ketmen (Uzynkara), Karzhantau, and Kuraminskiy ranges. There are also similar regions in the Gissaro-Alai and the western part of the Turkestan range. All listed mountain massifs are subjected to perennial freezing. Comparatively small deposits of permafrost that could be defined as island permafrost are located there.

Ground Ice and Icings of the Highlands

Ground ice

The shape and water balance of ground ice in the highlands is dependent on glaciers and perennial straight freezing of rock and sediments. The genesis of ground ice is characterized by a large diversity. Generally, ground ice can be separated into two main groups, i.e. buried ice and ground ice itself. In the first group, the ice is initially formed at the surface, and subsequently is buried in friable and segmental deposits, i.e. in moraines, under landslides, landslips, or under river and mudflows. Large monoliths of glacier ice are also among this type of ice (Figure 1).

Figure 1 *Buried glacier ice*

The volume of some of the largest ice massifs of this type reaches many hundreds of thousands m³. The majority of these types of ice deposits is confined to Holocene moraines. The age of these deposits is estimated at several hundreds or even thousands of years. Nevertheless, some buried ice can also be found in Late Pleistocene moraines. These deposits, for example inside mountain hollows (syrty) of the Inner Tien Shan, are of special interest, for instance in the Taragau River basin. Large thermokarst subsidence is spread at an elevation of 3500 – 3600 m. Some of them are still active, i.e. they continue to increase in size at the present time. All of them are confined to Late Pleistocene end- and ablation moraines of the ancient Prakumtor glacier. The age of the buried glacier ice deposits of these moraines is over 10,000 years. According to the size of the subsidence, the volume of the buried ice there can be estimated at many hundreds or thousands of m³ (Figure 2). The thermokarst depressions indicate that in the Holocene there was a period when the thawing of the buried ice ceased, probably due to a period of below average temperatures. At the present time, this process has started again, basically reflecting modern climate change. Thermokarst depressions in Late Pleistocene moraines can also be seen in some other places of the Inner Tien Shan. This type of buried ice is also present in the Eastern Pamir. The total volume of buried Late Pleistocene ice in the study region cannot yet be quantified.

Figure 2 *Thermokarst depression, appeared due to melting of the buried ice in the Late Pleistocene moraine.*

The buried glacier ice deposits in Holocene moraines, particularly the more recent ones, are studied on a larger scale. Buried glacier tongues should be treated separately from isolated buried ice deposits of glaciers that have lost or almost lost their mobility. Buried glacier tongues are generally buried under a relatively thin layer of friable materials often not thicker than a few meters. The latter ice deposits can be located at depths of several tens of meters. In contrast to the open ice parts of glaciers, buried massifs of ice are less susceptible to air temperature effects and, therefore, are preserved better. At the moment, there is a regularity being followed, i.e. the ice volume of mountain glaciers is decreasing, while massifs of buried glacier ice are increasing in volume due to the continued burial of parts of the degrading glaciers. A different environment containing significant massifs of buried ice is active rock glaciers (Figure 3) (Gorbunov et al. 1989). There are several thousands of them in the study region. It is not possible to differentiate buried glacier ice from ice of other origins in stone glaciers and to assess its approximate volume at the present time. That's a challenge for future research. In addition to buried ice in moraines and rock glaciers, there could be small massifs of buried lacustrine and icing ice, as well as buried avalanche snowfields, which might have been transformed into glacier ice.

Figure 3 *Active rock glacier.*

The other type of buried ice is can be defined as "real" ground ice. This is ice that developed during the multi-year straight freezing of friable, fragmental, and rock layers. It is differentiated by its morphological and genetic diversity. One type of ground ice is formed slowly through the straight freezing of moisture. These are segregation ice layers, lenses, and veins of different thickness. Another type develops from the straight freezing of invading subsurface water in closed spaces. This can be defined as injection and intrusive ice. Sometimes ice kernels are formed, whose volume can be estimated at many cubic meters (Figure 4). Infiltration ice is usually located in large, fragmental, porous deposits of some parts of moraines and rock glaciers, which are formed during the freezing of subsurface water as it is infiltrating into a zone with negative temperatures. It is also important to mention thermokarst and cavern ice, which are formed by the infiltration of surface water and the sublimation of atmospheric moisture. Wedge shaped ice and vein ice is formed in cracks of moraines and rock glaciers. They appear in thermokarst deformations as the results of some shifts of frozen ground, frost erosion or after earthquakes. Infiltration, segregation and sublimation processes participate in their formation. All mentioned processes produce ground ice in moraines and rock glaciers. Their total ice volume usually reaches and sometimes even exceeds 50 % especially in active rock glaciers.

Figure 4 *Injection ice in lacustrine deposits of Karakul (Eastern Pamir). Photo by V. Ratsek.*

Ground ice is not limited to moraines and rock glaciers. It also occurs in lake, alluvial, proluvial deposits, in curums, and highland talus. Lacustrine deposits and large segmental taluses and curums also may possess a significant ice content sometimes up to 50 %. Frozen slope deposits contain only small quantities of subsurface ice. Firstly, their ice holding capacity is not significant (tens of centimeters to a few meters), and secondly their ice content usually is not high, often only several percents (Gorbunov et al. 1981). Ground ice is also not confined only to friable and segmental deposits, but also may appear in rock massifs. The ice content within these massifs usually is not significant, though. However, the areal extent of the rock permafrost zone is many times larger than that of friable and segmental deposits. For example, in the Bolshaya Almatinka River basin (Northern slope of the Zailiskiy Alatau) the volume of the rock permafrost zone is 5.5 km³, while the friable and segmental permafrost zone is 1.3 km³. The ice content of the rock permafrost zone is about 1 %, while that of the friable and segmental deposits is approximately 30 %. The total volume of ground ice in the considered river basin is about 0.17 km³, while the glacier ice volume is 0.68 km³ indicating that the deposits of ground ice are about four times less than those of surface ice. At higher elevations, the volume of the rock permafrost zone is increasing, along with the deposits of subsurface ice in them.

The ice in rock massifs is not distributed evenly. The majority of the ice can be found in tectonic rock permafrost zones (Kagan et al. 1978). The width of the tectonic crushing zone usually varies from a few to several tens of meters. The extent of this zone depends on the strength of the rock structure. A weathering crust of several meters is observed in rock massifs. The strength of the rock massifs depends on the structure of layers, their shape, and many other factors, which also define the cryogenic texture and ice content of the ice deposits in them. If a crack free rock massif is ice free, and shows permanently negative temperatures, one speaks of dry permafrost . The average ice content of the rock permafrost zone is tentatively estimated at to 1 %. This, however, is only an approximate value and is rather underestimated than overestimated. The highest ice contents can be found in the zone of tectonic crushing where they can reach 20 – 30 %. Usually, it is represented by breccia ice cement. Almost all genetic formation processes of ground ice are represented in the crushing zone; infiltration, concrete ice, segregation, injection, and sublimation. Wedge-shaped ice deposits with a length of up to 20 cm can be observed in that particular zone. According to surveys, ice deposits of up to 0.5 m across can be found there. The ice content in weathering crusts varies from place to place with an average of about 5 %. Concrete, infiltration, and, sublimating ice is dominating in the crusts. In some mountain regions the ice capacity varies from 5 to 50 m (Kagan et al. 1978). It should be noted, that all mentioned quantitative estimates are approximate values as there are only few studies available. At the present time, the most neglected zone in scientific studies is the rock permafrost zone, especially its structure, ice content, and temperature characteristics. Furthermore, there is not much information on sub-glacier permafrost zones. It is assumed that such zones are absent under the largest glaciers. Information on the cryogenic structure of moraines, Late Pleistocene sediments, as well as active, non-active and ancient rock glaciers is very scarce. The situation is slightly better for perpetually frost in lacustrine and slope deposits.

It should be noted, that the amount of ground ice in the Tien Shan, Dzhnungar Alatau, Pamir and Alai, Saur-Tarbagatai and other ranges of the study region is very insignificant. The underground ice volume is approximately 4 times less than the surface ice volume. However, there undoubtedly has been a steady decrease of the surface ice volume, while overall subsurface ice volumes remained pretty steady so far. The recession of glaciers lead to the perennial freezing of sub-glacier talik systems, i.e. there is some increase of the permafrost zone and, therefore, ground ice. At the same time, there is some decrease in the area and volume of ground ice as the ice under disengaged small and middle size glaciers is decreasing, due to the fact that these deposits now undergo seasonal melt cycles. Erosion processes of fresh moraines are exposing ice massifs which subsequently melt forming thermokarst depressions. It is impossible to quantify the constructive or destructive processes of ground ice that result from the degradation of glaciers at the present time. More, especially long term, research is needed on this topic.

Icings

Large ice deposits (icings) are located in the North of the study region at elevations higher than 2000 m, while in the South they can be found above than 3500 m. Generally, the ice belt has a vertical extension of about 2000 m. Large ice deposits are defined as those whose area exceeds 10,000 m². These deposits dominate in that belt. Smaller size ice deposits which are rare in mid-elevation mountains are not considered in this study. Icings in the permafrost zone of the highlands are formed mainly due to under-freezing waters which emerge from transparent taliks. The last ones are usually confined to active tectonic cracks. A significant role in the feeding of icings is played by rivers and mainly by subsurface flows in river channel taliks. Small icings are formed due to the freezing of soil and surface waters. Large icings are often located in river valleys (Figure 5). They are called river valley icings. Some of them are directly connected to glacier tongues. Therefore, these icings are referred to as glacier, or sub-glacier icings. They are mostly fed by glacial melt water in rivers and subsurface aquifers. Subsurface water of transparent sub-glacier talik systems also takes part in their formation. In rare cases, epiglacier freezing can also be observed, sometimes blocking the surface of glacier tongues. Their formation is fully connected with subsurface, glacial melt waters. However, these ice deposits are not significant in their size.

Figure 5 *River valley icing in Tien Shan.*

As mentioned, the largest icings can be found in the river valleys of the highlands. For instance in the Terek River valley in the central Tien Shan the icing extends for 20 km with an average width of about 300 m. Its area at the time of maximal development reaches 5 – 6 km². The largest icing of the region is located in the Muzkola River valley south of the Karakul Lake (Eastern Pamir). Its maximum length reaches almost 10 km, with a width of about 1 km. The majority of the icings are concentrated in the Tien Shan and the Eastern Pamir. Formation conditions are optimal there, with a permafrost zone that is spread over large areas and low amounts of precipitation. The total area of the icings of this region in the most favorable years is close to 50 – 60 km². The total area of icings in the entire study region is about 80 km². Obviously, this assessment is an approximation; the values are most likely under- rather than overestimated. The thickness of ice in large icings is usually about 2 m, but sometimes can reach 4 m or even more than that. Consequently, the volume of the largest icings can reach many millions of m³, and all icings of the study region exceed 0.2 km³ in volume. The conditions of ice formation change from year to year. We have managed to collect some data on the development of the Muzkol icing. In most favorable years, it can last throughout the summer. Such years were more frequent at the end of 19th and in the first decades of 20th century.

Ground Ice and Icings of Saryarka

Ground ice appearing during deep season freezing is confined to inter-knoll decrease of Saryarka. Some are formed in hydro-force heels, that are called “tuma” by the local, Kazakh people. Others are formed as concrete ice in peat soils of wetland meadows and are locally called “saz”. The first type of ground ice consists of ice kernels, while the second type is characterized by seasonally massive ice beds. Ice body volume of hydro-force hills reaches 5 – 6 m³, and width of ice layers is a bit less than one meter. Hydro-free hills are most likely in inter-knoll lowering on east side from the mountains Ulytau (Borovikov 1974). Layer ice is discovered in the Akzhal and Akkain ranges, at 49 ° N., to the North of the Ulytau mountains, in the Karaganda district (Maslov 1966; Gorbunov 1989). It should be pointed out, that in the first part of the 20th century, the occurrence of seasonal ice and ice of pereletok in Saryarka was normal. Surveys conducted in 1970 did not discover any such ice deposits. Most likely this can be attributed to global warming and the change of the hydro-geological conditions.

Icings develop from the freezing of soil water in areas of little or no snow cover in depressions between hills. Such icings can be seen in from the South up to the foothills of the Zailiyskiy Alatau. These icings usually do not exceed several hundred m² in size. Its thickness is usually less than 0.5 m. The icings disappear completely during the spring. They are lrgely neglected by scientists up to the present time.

Conclusion

The perennial ground ice in the study region is confined to the highlands. They can be divided into two types (buried ice or subsurface ice) by their genesis. In contrast to glacier ice, ground ice is fairly stable. At the present time, ground ice only reacts weakly to global warming. The perennial freezing of sub-glacier taliks, which were disengaged from large glaciers during the glaciers recession leads to the formation of new massifs of ground ice. On the other hand, ice that is exposed in recessing moraines of small and medium size glaciers disappears due to thermo-erosion and thermo-abrasion. The decrease of glacier area combined with the relative sustainability of ground ice causes an increase in the number of mountain ranges, whose straight freezing will have only subsurface character. Basically, an increase of the subsurface portion of mountain ice takes place. At the present time, the total volume of ground ice in the study region is approximately assessed at 500 km³. It is approximately four times less than the volume of surface ice contained in all glaciers. However, this relation will go down to three times in the near future.

The most favorable conditions for the development of underground ice in the highlands occurred at the end of the 19th and in the first decades of the 20th century. During that period, most of the largest icings lasted throughout the summer. Currently, such a phenomenon can be rarely observed. The total area of the icings during their peak is estimated at 80 km².

The occurrence of seasonal and ice of pereletok of Saryarka was confined mainly to the first part of the 20th century. The conditions for the formation of these ice deposits have worsened during the recent decades.

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State of cryolitogen thickness of North Tien Shan

E.V. Severskiy

Results of geothermal monitoring over 32 years testify to differing reaction of multiyearly-and-seasonally frozen rocks to climate changes in different conditions of the Northern Tien Shan. A rise in temperature of 0.2 – 0.5 ºC in multiyearly frozen rocks has been noted during the period 1973 to 1995, after which it stopped. Their temperature has been retained at 0.2 ºC. during the last 11 years. Within 27 years the depth of seasonal thawing increased from 3.2 m in 1974 up to 6.0 m in 2001. Then it decreased in 2002, and in subsequent 4 years has been positioned within the limits of 4.6 – 4.9 m with small interannual oscillations. Reaction of seasonal freezing of strata to climate changes is different according to landscape-facial conditions. In low-hill terrain considerable changes of frost depth were not observed. Its interannual variability does not fall outside the limits of the measured oscillations.
In mid-hill terrain with a background of increasing winter snowfall and less severe temperatures, from 1974 to 1998, the tendency of frost depth reduction was recorded (25 cm on boreal, and 21 cm on austral slopes). Since 1999 to the present here the frost depth has been changed little. From 1975 to 1998, in high mountains (at an altitude of 3000 m) the changing of frost depth on slopes of different expositions has not been recorded. Its increase was marked during the last 3 years, 1.0 m at northern and 0.3 m at southern slopes.

Introduction

Monitoring of temperature regime both of multiyearly-and-seasonally frozen rocks and of a thawing layer is carried out in different landscape-facial conditions of the Northern Tien Shan from 1974 to the present. These data are the main and unique source regarding the condition and the changes of perennial and a seasonal frozen ground, not only for the Northern Tien Shan, but also as a whole for mountains of Central Asia.

Drastic changes of geocryological conditions occur in mountains as a result of local factors such as slope exposition, character of vegetation, and terrain structure. This occurs over rather short distances frequently overriding the influence of an absolute altitude. Records testify to differing reaction of multiyearly-and-seasonally frozen rocks due to climate changes under different landscape conditions. Continued monitoring will ensure evaluation of reaction to climatic changes and to develop forecasting techniques.

Investigations Results

Multiyear distribution of frozen rocks

The characteristics of multiyear distribution of frozen rocks and the features of spatial changes of depth and character of seasonal freezing of soils in the Northern Tien Shan are reflected in the regional structure of geocryological altitude zones (Figure 1) (Gorbunov, Seversky, 1979)

When distinguishing between zones with different types of permafrost distribution, the internal ratio of thawed and frozen layers had been taken into account. The total area of permafrost tracts in the sub zone with sporadic spreading amounts to not more than 1 – 2 %, it approaches 30 % at insular spreading, rises up to 70 % at intermittent distribution, and at solid state it is not less than 90 % of the sub zone's area. Separation of the sub zone with sporadic permafrost spreading is reasonable as it develops naturally in different mountain regions at positive average annual air temperatures in certain landscape facial conditions.

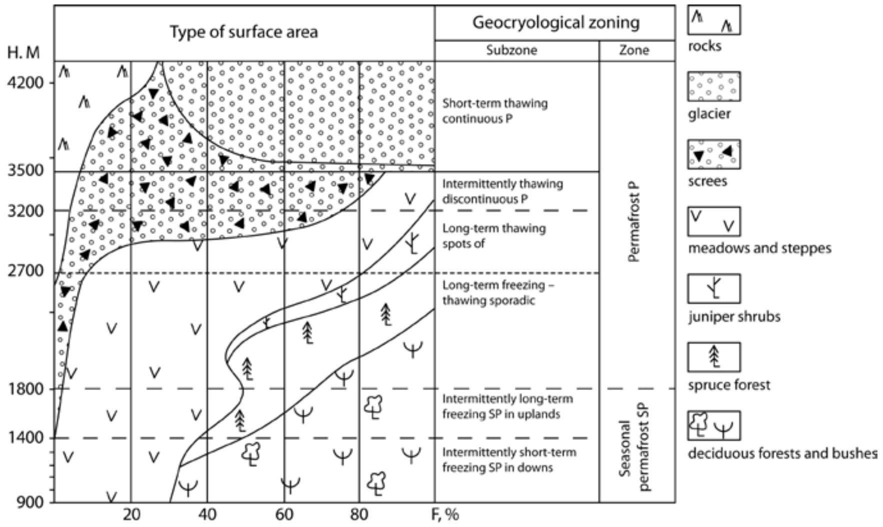

Figure 1
Geocryological zonality and landscapes of the Western Ile Ala-Tau Mountains (The Small Almaty River basin). Types of surface distribution are indicated according to Sosedov I. (1976) but with additions from the authors.

There are two sub zones within the belt of seasonally frozen rocks: resistant and unstable freezing. The last one is characterized by intermittence of frost penetration due to the melting processes taking place during thaws.

Typical changes in the structure of altitudinal geocryological zonality for northern and southern macro-slopes of the Ile Alatau Mountains are reflected in figure 2 (Gorbunov, Seversky, 2001).

There are no conditions for formation of local masses of permafrost on austral macro slopes; therefore the sub zone of a sporadic spreading is absent there.

Altitude borders of other sub zones are located 300–400 m higher in comparison to boreal slope.

Monitoring of cryolitogenous strata
An extensive network of fixed points for year-round geothermal observations, concerning MFR and SFR, presently exists in the Ile Alatau mountains. It encompasses different landscape facial conditions (Table 1)

In addition enroute geothermal probes are periodically conducted in different landscape conditions of low-hill areas and on submontane plains.

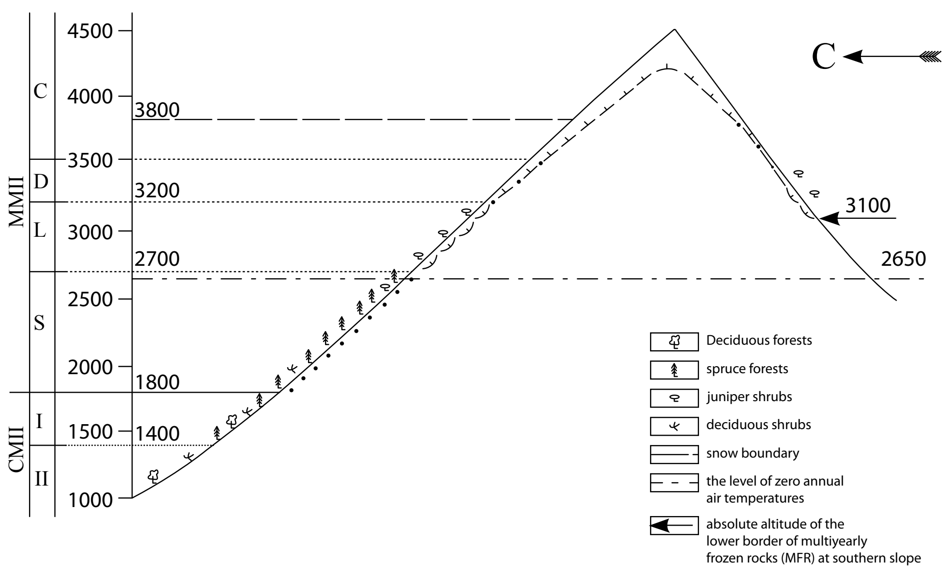

Figure 2
Geocryological zonality of the Ile Alatau Mountains. Idealized transverse profile. Scope of the geocryological belts and the sub zones. Multiyearly frozen rocks (MFR) of a: sporadic (S), insular (L), intermittent (D), and solid (C) permafrost distribution. Seasonally frozen rocks (SFR): mid-hill of a resistant freezing (I) and law-hill of an unstable freezing (II).

Table 1 Brief characteristics of the fixed points of thermometric observations

	Observation point	Absolute altitude, m	Exposition	Landscape-facial conditions	Period of observation
Sub zone of a sporadic permafrost distribution					
1.	BAL-1	2550	N	Loamy-macadam sediments. Subalpine meadow	1974 – 77; 1979 – 88; 1993 – 2006
2.	BAL -2	2570	S	Loamy-macadam sediments. Subalpine meadow	1974 – 77; 1979 – 88; 1993 – 2006
3.	BAL -3	2550	E	Loamy-macadam sediments. Subalpine meadow	1974 – 77; 1979 – 88; 1993 – 2006
4.	BAL -5	2550	NE	Loamy-macadam sediments. Spruce forest	1974 – 88; 1996 – 2006
5.	BAL -6	2550	NE	Loamy-macadam sediments. Subalpine meadow	1974 – 88; 1996 – 2006
6.	BAL -7	2570	E	Large lumps sediments. Without vegetation	1974 – 80; 1996 – 2006
7.	BAL -8	2610	E	Large lumps sediments. Without vegetation	1974 – 80; 1996 – 97
8.	BAL -11	2520	W	Rocky massive	1979 – 87; 2005 – 06
9.	BAL -12	2600	W	Land waste sandy sediments Herb meadow	1979 – 88; 1996 – 2006
10	BAL -13	2700	W	Large lumps sediments with Land waste sandy filling. Without vegetation	1978 – 83; 1985 – 87; 1996 – 2006
Sub zone of an insular MFR, SFR and permanent snow patch distribution					
11	BAL -14	3040	N	Loamy soils plus gruss, macadam and blocks. Alpine meadow	1975 – 87; 1996 – 2006
12	BAL -15	3040	S	Loamy soils plus gruss, macadam and blocks. Alpine meadow	1975 – 87; 1996 – 2006
13	BAL -16	2980	E	Loamy soils plus gruss, macadam and blocks, juniper shrubs	1975 – 87; 1996 – 2006
14	BAL -17	2980	E	Loamy soils plus gruss, macadam and blocks. Alpine meadow	1975 – 82; 1996 – 2006
Sub zone of an intermittent multiyear frost distribution					
15	Zhusaly 1	3330	horizontal	Blocky-macadam sediments with loamy-gruss filling	1973 – 77; 1990 – 2003
16	Zhusaly 2	3330	NE	Blocky-macadam sediments with loamy-gruss filling	1973 – 7; 1990 – 2006
17	Zhusaly 3	3330	horizontal	Blocky-macadam sediments with loamy-gruss filling	1973 – 77; 1990 – 2003
18	Zhusaly 4	3300	E	Loamy soils plus gruss, macadam and blocks. Alpine meadow. The surface of a soliflucton tongue	1976 – 82; 1996 – 2006
19	Zhusaly 5	3300	E	Loamy soils plus gruss, macadam and blocks. Alpine meadow, 1 meter from soliflucton tongue	1976 – 82; 1996 – 2006
20	Zhusaly 6	3350	S	Loamy soils plus gruss, macadam and blocks. Alpine meadow	1976 – 78; 1999 – 2006
21	Zhusaly 7	3320	W	Loamy soils plus gruss, macadam and blocks. Alpine meadow	1996 – 2006
22	Zhusaly 8	3320	N	Loamy soils plus gruss, macadam and blocks. Alpine meadow	1996 – 2006

Table 2 Mean values of active layer's capacity in Zhusalykezen saddle-point region, 3337 m

Year	1974	1975	1976	1977	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Seasonal thawing depth,m	3,2	3,5	3,3	3,5	4,90	5,0	4,85	4,45	4,95	4,95	4,80	4.90	4.90	5.10	5.0	6,0	4,6	4.8	4,9	4,6	4,9

Multiyearly frosted rocks (MFR)
Geothermal monitoring of MFR and a layer of seasonal thawing has been carried out in the Ile Alatau Mountains (the Northern Tie Shan) since 1974. Observations are conducted by a thermometric method in the chinks, located in area of saddle-point called Zhusalykezen over the range of altitudes from 3320 to 3340 m in the sub zone of intermittent permafrost distribution. Chinks are holed in the large-blocky massive of upper Pleistocene and Holocene moraines; volumetric ice content of those moraines varies from 5 % to 40 %. Dynamics of the cryolitozone in the Northern Tien Shan for the period till 1998 was summarized by Marchenko (2003).

Modification of MFR thermal regime for the last 32 years is shown in figure 3. In 1974 at the very beginning of the observation process the temperature of MFR was at 0.8 ° C below zero.
21 years later the temperature increased to 0.6 ° C. Finally, since 1995 up to the present time it has been around 0.2 ° C.

Seasonal thawing depth increased from 3.2 m in 1974 to 6.0 in 2001. But then that process has stopped. In 2002 it decreased to 4.6 m, and for the last 4 years it has been stable with minor interannual oscillations within the limits of 4.6 – 4.9 m (Table 2).

Seasonally frozen rocks (SFR)
Data from the many years of monitoring the temperature regime and the depth of seasonal frozen soils is presented in many publications: (Seversky and Seversky, 1990; Gorbunov et al, 1996; Gorbunov et al, 2000; Seversky 1996, 2001). The main characteristics of an average depth of seasonal freezing for the period from 1975 to 1996 due to different landscape-facial conditions of the Northern Tien Shan are presented in figure 4.

Results of investigations show differing change of depth and temperature under various landscape conditions at different altitudes for the 32-year period.

It is not possible to demonstrate consistent changes at given depths in low-hill terrain, due to insignificant freezing depth and essential interannual variability. A steady trend of reduction of seasonal freezing depth has been observed in mid-hill terrain up to the top forest border (from 1400 – 1500 to 2700 m) for the

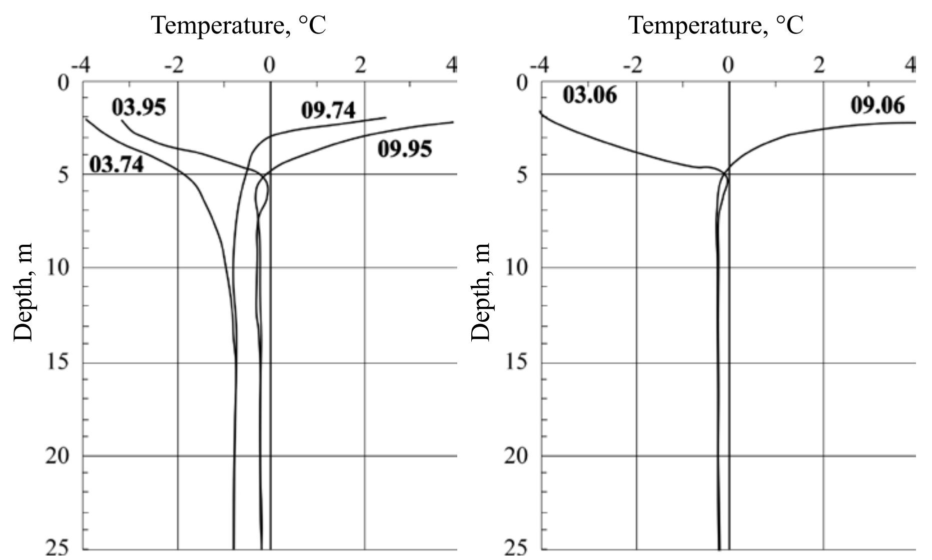

Figure 3
Temperature of MFR in the Ile Alatau Mountains at 3330 m for 1974 to 2006 as a function of depth (m)

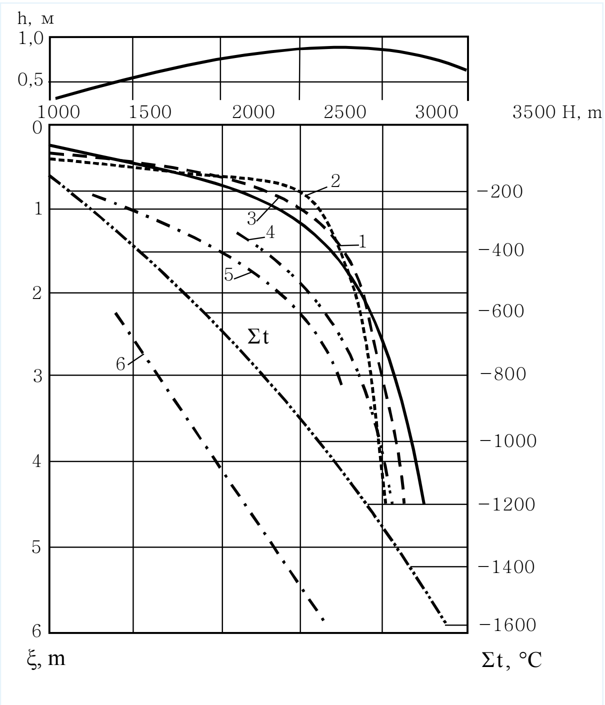

Figure 4 *Dependence of the snow depth (h), sums of negative air temperatures (Σ) and the depth of seasonally frozen soil (ζ) on altitude (H) in different landscape conditions of the Ile Alatau Mountains.*

1 – Southern meadow-steppe slopes;
2 –Northern meadow slopes;
3 – Eastern and western meadow slopes;
4 – juniper shrubs;
5 – spruce forests, under crown plots,
6 – large lumps sediments

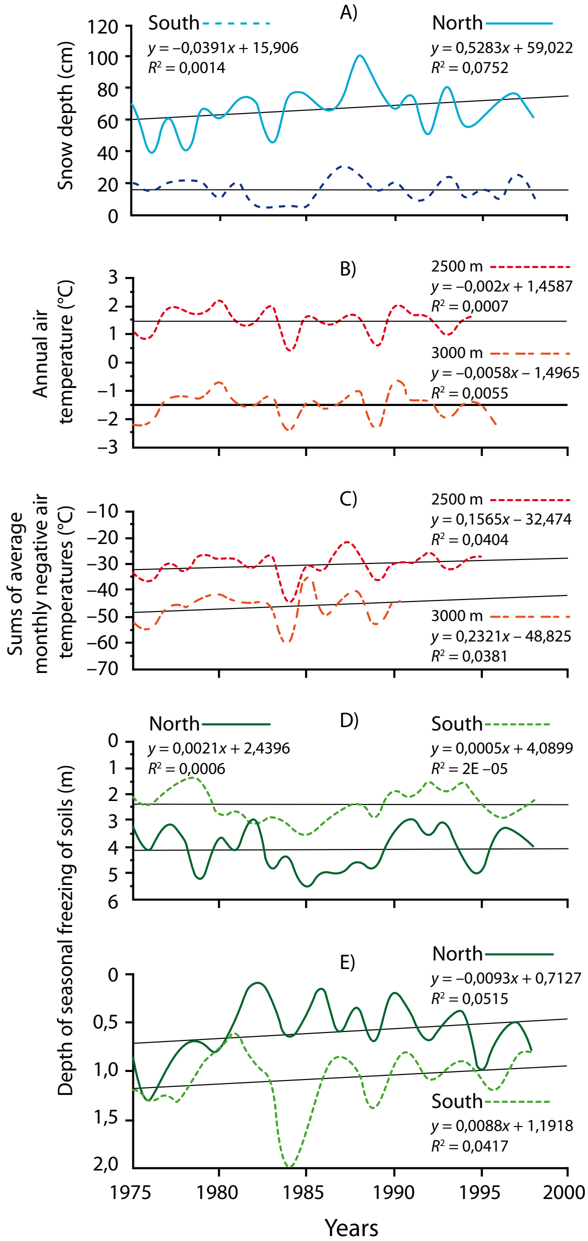

Figure 5 *Snow depth (A), annual air temperatures (B), sums of average monthly negative air temperatures (C) at altitude of 2500 m, depth of seasonal freezing of soils at altitude of 3000 m (D) and 2500 m., (E) their linear trends.*

period 1974 – 1998. Data comparing these values on two opposite, but otherwise equivalent, slopes in the central part of the Ile Alatau Mountains at 2570 m is shown. During the given period on loamy-macadam soils of the northern slope the freezing depth decreased to 25 m, and on the same ground on the southern one it reduced to 21 m. The trend of seasonal freezing depth reduction amounts to 1.1 cm per year for the northern slope and 0.9 cm a year for the southern one (Figure 5).

It is possible to infer 3 – 5 year periodicity waves of the reduction of freezing depth. Reduction of frost penetration coincides with increasing snowiness and reduction of winter severity. This is reflected in average monthly negative air temperatures (Figure 5). The trend of the reduction of temperatures is 0.2 °C a year, and there is a trend of increasing snowiness of 0.48 cm. a year for northern slopes. It is necessary to note, that the average annual temperature at height of 2500 m for the considered period has not changed, and its interannual variability remains within the bounds of natural fluctuations (Figure 5). It once again testifies that it can not be the reliable indicator of seasonal frost penetration depth. The sum of negative air temperatures is more reliable parameter.

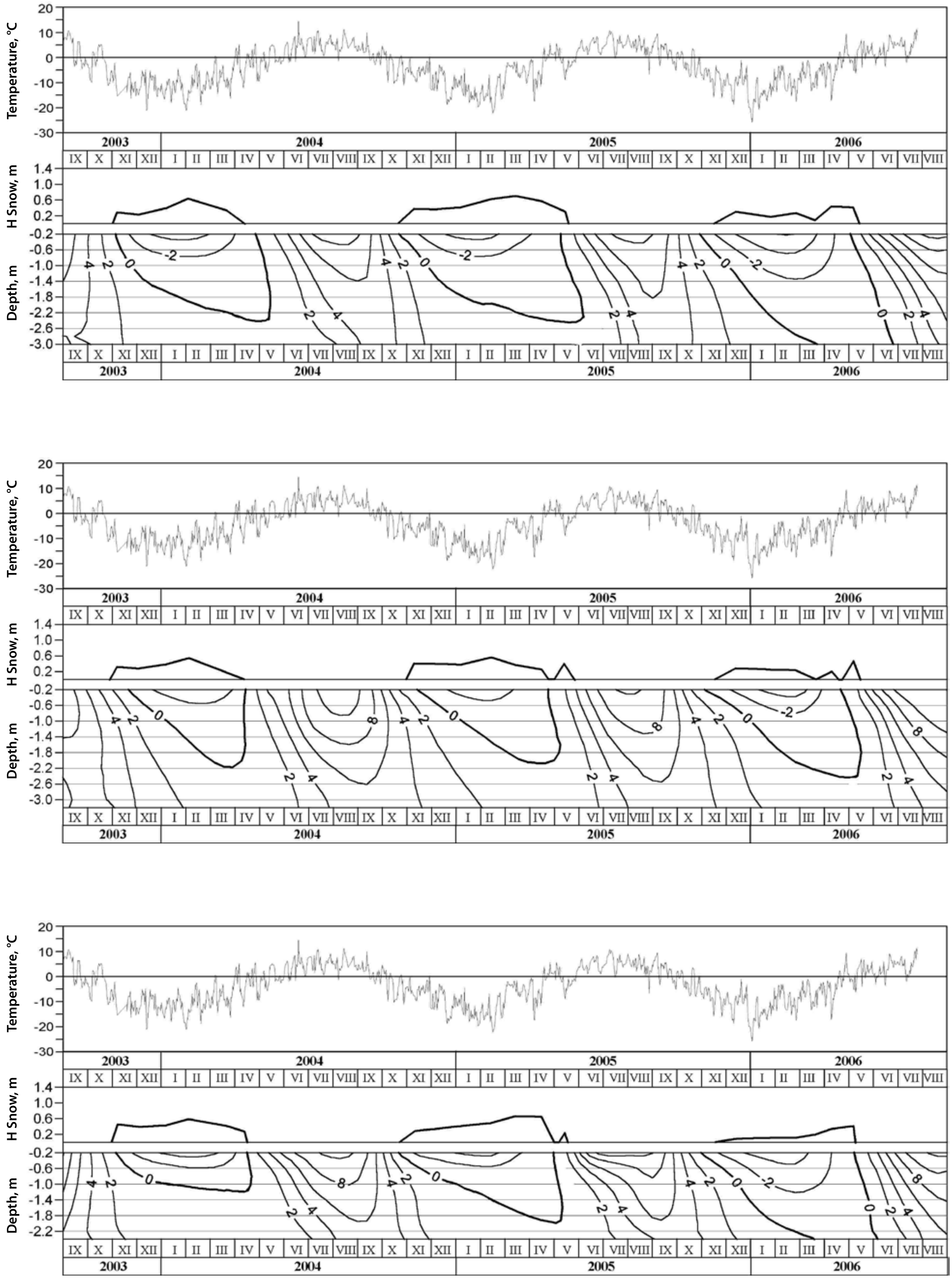

Figure 6 *Air temperature, snow cover depth and soil temperature on northern (top), southern (center) and eastern (bottom) slopes at 3000 m, 2003 to 2006.*

The revealed tendency of reduction of seasonal frost penetration depth for mid-hill terrains continued till 2002. It has been stable since 2003 and has been changing just slightly during the years. Under all other equal conditions, interannual fluctuations of freezing intensity and its depth depend of two factors: distinctions of soils temperatures before frost penetration, and terms ratio between the beginning of freezing and the formation of a snow cover (Seversky, 2001).

In high mountains, above 2700 – 2800 m, the northern slopes are in a zone of an active windy drift-snow transportation, which is forming by the way of compaction. Its height is 2 – 3 times less than a background here, and it frequently does not exceed 30 cm. On southern slopes the height of a snow is, on the average, 10 – 15 cm less. Here, as well as in low hill terrains, southern slopes always freeze through less, than northern ones, where sometimes permanent snow patches are forming.

The tendency in changing of frost penetration depth on northern and southern slopes during the 25-years period (Figure 5) was not shown for the period from 1975 to 1998, at a height of 3000 m. However, the increasing tendency of seasonal freezing depth on slopes with different expositions has been marked for the last 3 years. That is connected with the reduction of snowiness. Thus, it has increased from 2.4 m in 2004 up to 3.5 m in 2006 on northern slope, on east – from 1.2 up to 2.5 m correspondingly. On the southern slope, the figures indicated for these years have increased insignificantly by 0.3 m (Figure 6).

Cryogenesis on fresh moraines

Exploration of cryogenesis on fresh moraines, taking place in the recent years, is connected with the degradation of the Northern Tien Shan glaciation. On the basis of air photo analysis covering several years and of cartographic analysis, it has became possible to reliably infer rates and intensity of de-glaciation and also to demonstrate the changes, happened in the second part of the 20th century, in the structure of glacier-moraine complexes of 4 large glacial systems of the Northern Tien Shan, which had been forced by global climate warming (Vilesov et al, 2006). For the period from 1955/56 till 2004 the area of a glaciation in glacial systems of Kazakhstan's part of the Ile River's basin was reduced from 926.13 to 570.15 km², i.e. 356 km² or 9.23 km² per year (Vilesov et al, 2006).

For 50 years (from 1955 to 2004) the area of the glaciers of the Ile Alatau northern slope (where left basins of the Ile river are located) has reduced by 117.26 km², ie 40.8 %. An average velocity of such reduction has made about 3.0 km² or 1.05 % per year (Vilesov et al, 2006). Dry and hot weather of the summer of 2006 promoted increased melting of glaciers and their further degradation. So, the Central Tuyuksu glacier, situated in the Ile Ala Tau mountains within the Small Almaty River basin, has receded almost 1 km distance in the period 1958 – 2006 (Figure 7).

Glacier recession in the Tien Shan leads to moraine sediments transferring from subglacial to the sub aerial status. This process essentially changes conditions from cryogenic and post cryogenic processes on fresh moraines. When small glaciers recede, permafrost moraine layers are uncovered. In subaerial conditions they are subjected to thawing to 1 – 2 m depth from the surface during summer seasons, i.e. the layer of seasonal thawing appears which was absent in the presence of subglacial conditions.

As large glaciers recede long-term frost penetration of the transparent and blind talik systems occurs alongside the above-mentioned process. Transformation of the moraines from subglacial to subaerial condition results in changes in relief; new processes and effects appear. There is an especially distinguishing thermokarst modification. These are caused mainly by thawing of buried glacier ice and high ice-covered massifs, which are unearthed from the moraines by means of water from melted glaciers. Cryogenic landslips result in similar consequences as they reveal buried ice, ice-cored moraines or lacustrine sediments.

The thawing of buried ice, accompanied with partial thawing of permafrost moraines, leads to subsidence cavities which are filled usually with the water from melted snow. In this way thermokarst lakes form. Some of them exist for a long time, others disappear in a few years and yet others are filled with water only in summer, and are drained in winter. Some subglacial lakes originate from damming by sediments of cryogenic landslips. Thus, fresh moraines are the arena for intensive formation of lakes of various genesis, size and configuration. So, there was only 10 lakes, (each with capacity of over 10,000 m³), in the mid 1960s on the northern macroslope of the Ile Alatau. In 1980 their number increased to 41 (Popov, 1986), and by 1990 to 60. In the last 10 years aerovisual

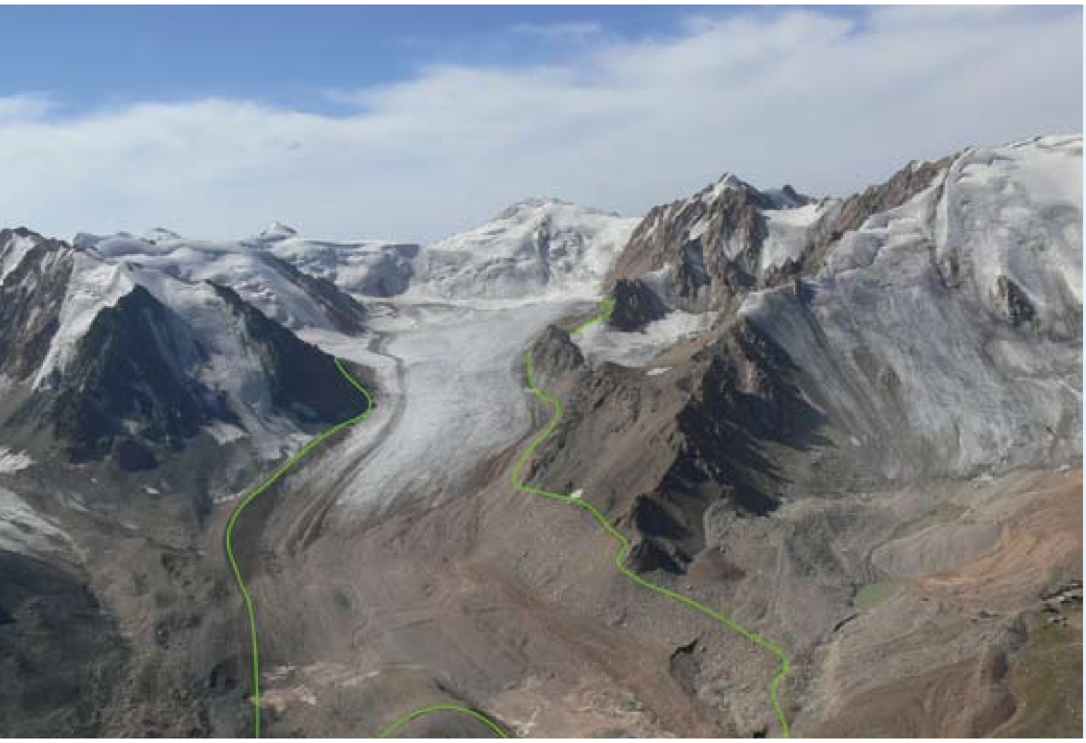

Figure 7
The Tuyuksu Glacier (photo August 16, 2006). The outline shows glacier extent in 1958.

monitoring of the glacial belt testifies that their quantity is much more than earlier. In many cases a break of the largest lakes results in large and small glacial floods.

In addition to the lakes, soliflucton processes are developing on fresh moraines, and also active rock glaciers are forming. Loose-fragmental deposits of fresh moraines increase the supply area of rock glaciers. Frazil ice is uncovered and destroyed, pattern grounds are formed, and frost weathering processes are activated on fresh moraines. Intensive cryogenic processes of the frozen and thawed layers, originating from a glacial cover, are taking place. Such processes have not been investigated properly as yet. But they, undoubtedly, should take a worthy place in sphere of geocryological research. Monitoring of cryogenic transformation of loose-fragmental cryolitozone is especially important. Such works have practical as well as theoretical value, in particular, for water management decisions, particularly for actions to prevent or minimize the risks of glacial floods.

Conclusions

Results of geothermal monitoring of multiyearly-and-seasonally frozen rocks and also of a seasonal thawing layer have been stable in high mountains (at 3337 m); during the last 11 years, their temperature has been steady around –0.2°C.

It was revealed that seasonal thawing depth extended from 3.2 m in 1974 up to 6.0 m. in 2001 here, but thereafter it stabilized and for the last 5 years it remains around 4.6 – 4.9 m. with slight interannual variation.

There is a tendency of a seasonal freezing extension at altitudes of more than 2700 m in the sub zone of insular permafrost spreading, taking into account different exposition of the slopes. Because of decreasing snowiness which took place during the period 2004 – 2006, freezing depth rose from 2.4 to 3.5 m on boreal slopes and from 2.2 to 2.5 m on austral slopes, and from 1.2 to 2.6 on eastern slopes.

There is a trend, beginning in 2003, to stabilize the depth of ground freezing in different landscape conditions of a mid-hill terrain in sub zone of a sporadic permafrost distribution. Depth of seasonal freezing here is close to an average perennial magnitude. Interannual variability of frost depth in many respects is defined by conditions of the prewinter season, such as ground temperature before freezing and the time difference between the beginning of freezing and establishment of snow cover.

Reduction of glaciation in the last decades in the region considered characterizes circumstances peculiar to the entire Tien Shan. It can be assumed that glaciation on the boreal slope of the Ile Alatau will practically disappear by the end of XXI century, and in the Southern Dzhungaria it can happen in 40 years (Vilesov and Uvarov, 2001). In other areas (head-streams of the Chilik and Tekes rivers) large glaciers will be reduced considerably but will remain for a long time. It is possible to establish confidently, that to the middle of streaming century, fresh moraines will be larger than the nearest glaciers. These moraines become areas of constantly intensifying cryogenic and postcryogenic activity. Thus the risk of glacial floods increases significantly. It is reasonable to assume that the time of intensive formation of rock glaciers has started. Therefore it is necessary to practice in every possible way constant monitoring of cryogenous processes on fresh moraines as well as monitoring of glacial systems. Year by year the problem is becoming more and more critical.

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Glaciers of Central Asia: current situation, changes and possible impact on water resources

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Recent glaciation changes of the high mountains of Asia have impacts on runoff of melt water from seasonal flow, firn and ice. Present trends show additional runoff from glaciers with stable mass balance. Range and long-term trends of mass balances are shown. Future impacts an surface water runoff are discussed.

Introduction

The topics of water availability and possible consequences of global warming on water resources are of highest priority for the countries of Central Asia. For the last decades, water safety has been one of the basic challenges in the framework of sustainable development nearly all over the globe. A relatively good situation concerning water availability for population and economies of the world in the beginning of the 1950s (Shiklomanov 1998) suddenly changed for the worse within the following decades. In the 1960–1970s the global programmes "The International Geophysical Year" (1957–1958) and "The International Hydrological decade" (1965–1974) revealed rather unfavourable trends in the development of water availability for the population and economies on practically all continents. Since then, the attention of scientists and of the international community to water issues has increased. During the last decade, research within the framework of more than 50 international programmes has been simultaneously carried out. All of the programmes were either directly or indirectly aimed at the solution of water safety problems. The following large-scale programmes are among them:

- International Hydrological Programme (IHP)
- The Man and Biosphere (MAB)
- World Water Assessment Programme (WWAP) – UNESCO
- Water, Environment and Sanitation Programme (WES) – UNICEF
- Global International Waters Assessment (GIWA)
- Global Environment Monitoring System, Freshwater Quality Programme (GEMS/WATER) – UNEP
- Water resources, development and management for agriculture
- Integrated Land and Water management – FAO.
- Water Resources Management
- Water supply and sanitation – WB
- Water, Sanitation and Health Programme (WSH) – WHO
- Hydrology and Water Resources Programme (HWRP) – WMO.

Such attention to the issue of water can be attributed to the fact that about 80 countries in the world, representing 40 % of the world population, are under severe water stress. The situation may worsen in the forthcoming 50 years due to further population growth, global warming, and precipitation changes (Water for People 2003). 20 % of the world's population has no adequate access to drinking water and 50 % have no access to a central system of water supply and canalization. In Asia, 700 million people, representing almost half of the population, have no adequate water supply and 180 million people are devoid of adequate sanitary facilities (WWDR1 2003).

According to the results of a group of international experts, the deficiency of fresh water quickly increases with the development of the population and economy: between 1900 and 1995 water consumption increased 6 – 7 fold, which is twice the rate of the global population growth. In 1995, the total world water withdrawals were 3750 km³/year, with water consumption reaching 2280 km³/year. Taking into account forecasts of economic development, population growth, and climatic change, water withdrawals by 2025 could reach, by different estimations, 4600 – 7000 km³/year. It is also expected that by 2025 the use of water will increase by 15 – 35 % in the developed countries and by 200 – 300 % in the developing ones (Shiklomanov 1998). The achievement of the "Millennium Development Goals" of providing the population with drinking water will represent the main expenditure in all countries and will reach 10 to 30 billion USD a year (WWDR1 2003, WWDR2 2006).

A major part of Central Asia is located in an arid zone. Consequently, many Central Asian regions are experiencing fresh water deficiencies. Even now, a majority of the temperate latitudes territory in the northern hemisphere, including Kazakhstan and the adjacent countries of Central Asia, is under extremely severe water stress. The rate of water resources use has exceeded 40 % here and continues to increase quickly. According to the same report, the increasing water deficiency can result in "a series of local and regional catastrophes and collisions likely to lead to a crisis on a global scale" (ICG 2002).

A great number of scientific publications appeared over the past 15 – 20 years expressing serious fears about the significant reduction of water resources in the arid areas of the world as a reaction to a continuous global warming. One of the arguments substantiating such forecasts is the indisputable fact of a continuous rapid retreat of glacier ice. During the period of 1956 to 1990 alone, glacier resources in the mountains of Kazakhstan and the adjacent countries of Central Asia receded by more than a third. This process is still continuing with glaciers receding at an average rate of about 0.6 – 0.8 % per year by area and of about 1 % per year by ice volume (Sarsenbekov et al. 2004; Severskiy et al. 2006). If these trends continue in the future, the glacial ice in the mountains of Kazakhstan will disappear by the end of this century (Vilesov & Uvarov 2001). The resulting changes in the hydrological cycle would be substantial, since the contribution of glacial melt water to rivers originating in the mountains can be as high as 25 % of annual runoff and up to 50 % of total runoff during the growing season. For example, glacier runoff is responsible for 40 – 50 % of annual discharge in the Tarim and Balkhash basins (Dolgushin & Osipova 1989). For the whole Tien Shan, the annual and summer fractions of glacier runoff are 20 % and 35 %, respectively (Aizen & Aizen 1997; Aizen et al. 1995; Aizen et al. 2006)

The assessment of the present and estimated changes of glaciation in Central Asia has a basic importance for two reasons. Firstly, glaciers are clear indicators for climate change: the current rate of average annual temperature increase of less than 1.0 °C per century was sufficient to reduce glaciation in the mountains of Central Asia and Kazakhstan by more than a third. Secondly, it is important to estimate the impact of the present glacier retreat on river streamflow and water resources especially in Central Asia, where population grows rapidly and water availability for the population and the economy is exceptionally important.

Water and water safety

The rational use of water resources constitutes one of the main points in the modern strategy of sustainable development on a national level. The issues of a joint use of water resources in transboundary basins are frequently becoming the cause of conflicts. Central Asian countries are no exception in this respect. On the contrary, during the last decades the situation concerning water availability became more pressing in the region (UNEP 2005). Presently, the economies of the countries in the region are developing rapidly, contributing to an increasing water resources deficiency (Severskiy 2004; SPECA-Report 2004, UNEP 2005).

About 40 % of the territories of the five CIS countries, Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan and Tajikistan, belong to the basins of two internal-drainage reservoirs – the Aral Sea and Lake Balkhash. These regions sustain 80 % of the population and represent the overwhelming part of the irrigated land within these countries. Consequently, the issue of water in this region is particularly urgent (ICG 2002; Severskiy 2004; SPECA-Report 2004). The most severe situation has developed in Turkmenistan and Uzbekistan as 80 – 90 % of their economies depend on water resources withdrawn from transboundary rivers originating in neighboring countries. Uzbekistan has, per capita, less than 2500 m³/year freshwater.
It should be noted, that water availability of less than 2000 m³ p^{-1} year^{-1} is considered very low, and less than 1000 m³ p^{-1} year^{-1} catastrophically low (UNEP 2005; WWDR1 2003) .

The complexity of issues connected with a joint water resources management in shared reservoirs was most vividly revealed in the basin of the Aral Sea, where the vital interests of Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, Turkmenistan, Afghanistan and to some extent Iran are intertwined. According to specialists of the regional countries and international experts (SPECA-Report 2004; UNEP 2005), the issue of water resources management is the key topic for a sustainable development. Though the governments of the countries in the region and the international community undertake certain efforts, the situation concerning the water supply for the population and economies of Central Asian countries remains tense and shows signs of getting even worse (UNEP 2005). The causes are evident with the most significant being:

- The transboundary character of the main watersheds of the region forcing interstate coordination efforts towards rational water resources management;
- The system of water resources management in the transboundary basins, which was founded on the principles of a centralized regulation created in the soviet period, is imperfect;
- The low efficiency of irrigation canals combined with limited financial and technological resources in the countries of the region which do not allow the large-scale reconstruction of irrigation systems;

The situation is further complicated by the internal problems of the region, the most important of them being (UNEP 2005) the lack of clearly defined national water strategies and a mutually acceptable legislative base for the interstate management of shared water resources. The total runoff in the Aral Sea basin constitutes not more than 148.5 km³/year, 116.5 of which is river streamflow (UNEP 2005). The natural water resources in the Aral Sea basin are already fully exhausted and the further development of the economy of the region will result in a growing water deficiency. At present, total withdrawals reach 130 – 150 % in the Syrdarya river basin and 100 – 110 % in the Amudarya river basin (Kipshakbaev & Sokolov 2002; UNEP 2005). More than 90 % of the regional water resources are used for irrigation.

The situation in the Balkhash basin is hardly better. The negative trends seen in the Aral Sea basin are to some extent also present here. In spite of an agreement between Kazakhstan and China a future considerable reduction of the river Ili runoff from the Chinese territory is inevitable due to the projected drastic population growth and known plans of the use of water-energy resources on the Chinese part of the Ili river basin (Aizen et al. 2006; Giese et al. 2004).

There is also an immense water stress in the Xinjiang Region in Western China. The river runoff in Xinjiang amounts to 88.5 km³/year, 52.5 % of which is coming from the Tien Shan, 29.4 % from Kunlun Shan, and 18.1 % from the Altay and Dzhunghar Alatau mountains. These resources are shared equally by South and North Xinjiang. Together with the river resources drained from the territories of the other countries, the total sum of runoff in Northern Xinjiang where the rivers Ili and Irtysh originate is estimated at 43.9 km³/year. 22.1 km³/year of this runoff reach Kazakhstan in the rivers Irtysh, Ili, and Emel, thus reducing the amount of usable resources of river runoff in Northern Xinjiang to 21.8 km³/year (Giese et al. 2004). As in all parts of Central Asia, the overwhelming part of Xinjiang discharge (up to 70 %) is generated by the melt of snow and ice resources and up to 75 % of the annual runoff is concentrated from June – August. Similar to the situation in the Aral Sea basin, the resources of the natural runoff here are almost fully exhausted. 84 % of the total available runoff had been used by 1991. The remaining 16 % is in fact a reserve stock indispensable for the ecosystem of the flood-plain woodland and for the control of the intensifying processes of desertification in the lower reaches of the rivers. By 1993, the amount of water used in agriculture was 94 % of total water withdrawals (Giese et al. 2004).

Water resources management in both countries of the Aral Sea basin and Xinjiang region are characterized by huge (up to 50 %) losses of water in irrigation systems due to the prevalence of archaic irrigation technologies. The degradation of natural landscapes and desertification of these territories is quickly reaching a threatening scale. The conflict of interests between water users in the upper and lower reaches of the rivers is also very acute here, with irrigational agriculture on the one side, and industry and urban services, on the other (Giese et al. 2004).

The issue of water security in the countries of Central Asian region is clearly acute as all big rivers of the region are transboundary, with the biggest of them, the Amudarya, Irtysh and Syrdarya rivers, crossing the borders of three and more countries. This is a peculiarity of the region and one of the reasons for developing integrated efforts of Central Asian countries aimed at a peaceful and ecologically balanced management of the water resources of the region.

Besides the possible changes in water resources caused by climatic factors, most of which are unfavorable for agriculture, the priorities of integrated water resources management are defined by the following factors:

- unequal spatial distribution of discharge: nearly 68 % of the renewable water resources of the Aral Sea basin originate from the territories of Tajikistan and Kyrgyzstan, while major areas of irrigated land using more than 90 % of total river runoff volume are situated in Uzbekistan, Turkmenistan and to a lesser extent Kazakhstan
- conflicts of interests between hydro-energy projects and agriculture relying on irrigation
- imperfection of the system of water distribution
- high year-to-year variability of river runoff

The urgency of the situation is further accentuated by the very unfavorable projections which state that as a result of global climate warming, the water resources of the main river basins, including the Amudarya, the Syrdarya, the Ishim, and the Tobol, will decline by 20 – 40 % in the coming decades (Chub 2000, Sorokin 2002, Ramazanov 2004, Golubtsov et al. 1996, Skotselyas et al. 1997). Under such circumstances, studies of present and estimated changes in the characteristics of the snow cover and glaciation, which are the main sources of regional water resources recharge, are becoming more pressing. One of the key tasks of these studies is the monitoring of glaciers combined with projections of glaciation dynamics in the foreseeable future and their possible impact on the regional water resources.

Climate Change in Central Asia

Climate change issues have always attracted the attention of scientists, but in the 1970s the discussion became public on a global scale. The major results of climate change studies are summarized in the reports of the Intergovernmental Panel on Climate Change (IPCC) which estimated, that the average global air temperature increased by 0.3 – 0.6 °C during the 20th century, while the level of the worlds oceans rose by 10 – 20 cm (IPCC 2001). In Kazakhstan the rates of increases in average annual and seasonal temperatures are much higher than the global average. For the second half of the last century (1954 – 2003) alone, the average annual air temperature in the territory of Kazakhstan has grown by 1.5 °C (almost exclusively due to an increase of winter temperatures), but the rates of warming in various areas of Kazakhstan for the specified time period differ extensively – from 0.7 °C in the southwest (Aktau) to 2.0 – 2.5 °C in the east (Pavlodar, Semipalatinsk) (Dolgikh 1995; Eserkepova et al. 1996; Bultekov et al. 2006). It is estimated that the concentration of CO_2 in the atmosphere will double and the resulting rate of annual temperature growth will be about 0.2 – 0.4 °C/decade by the middle or the end of the present century (IPCC 2001). Another reaction to climate warming is a possible shift of climatic zones towards higher latitudes, leading to massive changes in the ecosystems (Budyko 1987; Muminov & Inagamova 1965; Budyko & Groysman 1991, Price & Barry 1997, Guisan et al. 1995) and considerable economic losses (Voronina 1997; Faizov & Asanbaev 1997; Chichasov & Shamen 1997; Spektorman & Yu 1999; Golubtsov et al. 1996; Gossen et al. 1997; Mizina et al. 1997).

Future climate projections are based on greenhouse gas emission scenarios. During the last 200 years, the concentration of the main greenhouse gases has increased significantly: CO_2 by 70 ppm or 25 %, CH_4 by 0.75 – 0.80 ppm, or 100 %, N_2O by 0.30 – 0.35 ppm, or 8 – 10 %. Meteorological observations are documenting climate fluctuations in the Northern hemisphere for the last 100 years. Air temperature anomalies are often connected to changes in atmospheric flow patterns and the dominance of zonal or meridional circulation, with a relative increase of zonal flow

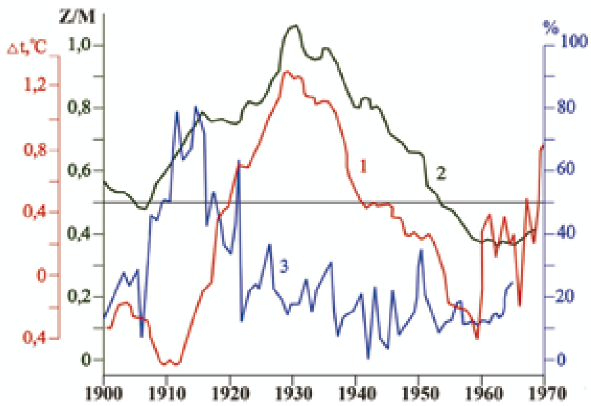

Figure 1 *Long-term dynamics of: 1 – air temperature anomalies, Δt in the latitudes 87,5 – 72,5° N; 2 – duration ratio of zonal to meridional processes, Z/M; 3 – the percentage of advancing and stationary glaciers of Switzerland, %*

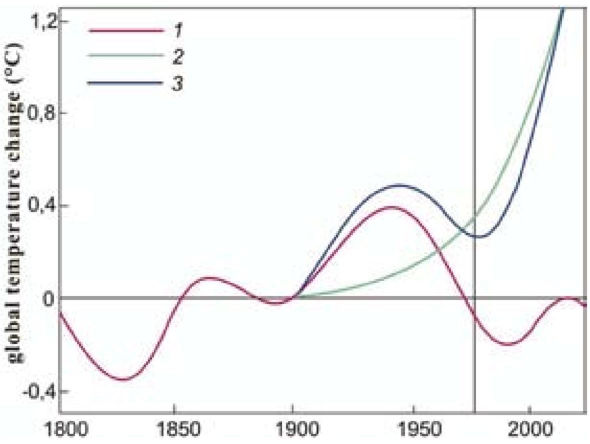

Figure 2 *Global temperature changes in 1800–2050 (according to Broecker 1975, abridged): 1 – natural temperature cycles; 2 – global temperature changes due to the greenhouse effect* CO_2*; 3 – combined effect of factors 1 and 2*

patterns generally leading to a significant warming (Figure 1) (Kotlyakov 2004, 2006). The generalized character of global temperature changes can be seen from the data of figure 2.

Line 2 in figure 2 shows the impact of anthropogenic factors, amongst which the dominant role is attributed by climatologists and geologists to the increase of dust and CO_2 in the atmosphere. The actual temperature increase is displayed in line 3, showing the sum of line 1 and 2. That line indicates that the main factor responsible for the warming trend during the first 40 years of the 20th century was a natural temperature cycle, with the contribution from the greenhouse effect of CO_2 hardly reaching 20%.

During the next 40 years the natural temperature graph shows temperature decreases, while at the same time the level of CO_2 concentration in the atmosphere continued to rise causing a fourfold temperature increase (from 0.1° to 0.4°C). These two opposite trends balanced each other and little temperature change was observed as a result.

During the subsequent 40 year period, i.e. from the 1980s to the first quarter of the 21st century, the natural decline of temperatures was replaced by a warming cycle, while the anthropogenic greenhouse effect further increased the average global temperature resulting in temperatures that were never reached during the last millennium. If the fossil fuel consumption is not reduced, air temperatures will continue to increase and, consequently, will influence the equilibrium of the main water reservoirs on the planet, oceans and glaciers (Kotlyakov 2004; IPCC 2001).

Current Glaciation Dynamics

Glacier monitoring

Regular observations of glacier changes first started in Switzerland in the 1870s and afterwards gradually spread into other glaciated mountain regions. In 1894, a Glacier Committee whose sole purpose was the study of glacier changes was founded at the VI International Geological Congress. In 1960, a new programme of observation of glacier changes was created, and in 1967 a permanent office for the synthesis of the results of global glacier monitoring was installed and later transformed into the World Glacier Monitoring Service (WGMS). In Russia, observations of glacier changes in the Caucasus, the Altay, and the mountains of Central Asia were carried out starting in the 19th century and comprised mainly the monitoring of snout positions. In 1963, the USSR started observations of changes on nearly 200 glaciers on a permanent basis. In 1973, a new programme including three types of glacier observations was initiated: detailed year round observations on a number of glaciers permitting the investigation of the basic characteristics and processes in the glaciers (first class), observations of the periodical changes of the main parameters of some glaciers (second class) and more large-scale periodical observation of glacier snout positions.

Modern glaciology distinguishes four types of glacier changes (Kotlyakov 2004), the two main ones being: 1) externally forced changes caused by changes in the accumulation and ablation and 2) auto-fluctuations characterized by abruptly pulsating movements (inner movement). The mechanism of forced changes is being studied by observing glacier-atmosphere interaction as well as the inner mass and energy exchanges of glaciers. Very thorough, unprecedented, research was carried out in the 1960s–70s on the glaciers Obrutchev (Polar Urals), Shumskiy (Dzhunghar Alatau), Central Tuyuksu (Zailiyskiy Alatau), and Abramov (Gissar-Alay) (Kotlyakov 2004). In the 1940s, annual mass balance monitoring started on a number of selected glaciers, including the glacier Central Tuyuksu in the Zailiyskiy Alatau, and proceeded to become large-scale with the beginning of the work during the International Hydrological Decade (1965–1974) and the following International Hydrological Programme.

The sum total surface of the glaciers in Asia is estimated at 120,560 km² (Dyurgerov & Meier 2005). 3,500 km² of them belong to Central Asia and Siberia and 116,180 km² to the high Asian mountains. The largest glaciation is concentrated in the Himalayas (33,050 km²), the Karakorum (16,600 km²), the Tien Shan (15,417 km²), the Pamir (12,260 km²) and the Kunlun Shan (12,260 km²). Table 1 presents information on those glaciers of Asia and the Northern Caucasus on which long-term monitoring of mass balance was performed.

Table 1 shows that only 18 glaciers have mass balance records of more than 20 years. Unfortunately, on 12 of them monitoring was stopped at the beginning of 1980–1990s. At present, only five glaciers of the high Asian mountains are being monitored. Three of them are in the Altay and two in the Tien Shan. The longest monitoring is carried out on the Central Tuyuksu glacier, which has been monitored for 50 years including the records of the glaciological year 2005/2006. The duration of continuous monitoring of mass balance on Glacier No. 1 in the Eastern Tien Shan and on the Maly Aktru glacier in the Altay is only a little shorter (Table 1). Unfortunately, monitoring of the Abramov glacier was terminated. This glacier is the only one in the Pamir-Alay region, on which

Table 1 The glaciers of Asia and the Northern Caucasus with the longest periods of mass balance monitoring

Region	Glacier	Glacier surface, km²	Period of Supervision		Time series, years
			start	end	
Caucasus	Djankuat	3.10	1968	—	36
	Garabashi	4.47	1984	—	20
Altay	L. Aktru	5.96	1977	—	27
	M. Aktru	2.73	1962	—	42
	№125	0.75	1977	—	27
	P. Aktru	3.88	1980	1990	11
Pamir	Abramov	22.50	1967	1998	31
Tien Shan	C. Tuyuksu	2.66	1957	—	47
	Igli Tuyuksu	1.72	1957	1990	34
	Molodozhny	1,43	1957	1990	34
	Mametov	0.35	1957	1990	34
	Kara-Batkak	4.56	1957	1998	42
	Golubina	5.75	1969	1994	26
	Urumqi No. 1	1.74	1959	—	45
Dzhunghar Alatau	Shumskogo	2.81	1967	1991	25
Polar. The Urals	IGAN	0.88	1958	1981	24
	Obrucheva	0,30	1958	1981	24
Kamchatka	Kozelski	1.79	1973	1998	25
Himalayas	Changmekhan	4.50	1981	1986	6
	Dunagiri	2.56	1986	1990	5
	Shaune Garang	4,94	1982	1990	9
	Gor Garang	2.00	1977	1984	8
Tibet	Xiaodongkemadi	1.77	1989	1998	11

Source: (Dyurgerov & Meier 2005). Note: (—) signs in column 5 mean that the observations continue.

complex glaciological and hydro-climatological observations including an annual glacier mass balance determination were carried out during 31 years. Furthermore, monitoring was also terminated on the Kara-Batkak glacier in the Tien Shan, which continued for 42 years, and on the Shumskiy glacier in the Dzhunghar Alatau, as well as on the glaciers of the Polar Urals and Kamchatka, which continued for 24 – 25 years.

In fact, the inventory of glacier monitoring presented in table 1 includes all of the observational data that could be of interest for research on mass balance changes in Asian glaciers. Additionally, during 1970 – 1990s mass balance measuring was carried out on 38 more glaciers of Asia, including three glaciers in the Altay and 11 in the Tien Shan, but the duration of these monitoring ranges only from one to nine years. This shows that the data for a well-founded assessment of present and projected dynamics of glaciation in Asian mountains are very scarce, especially in the mountain ranges of Tibet, Pamir, Himalaya, and Kunlun. Mass balance data of the Hindu Kush-Karakorum glaciers do not exist. Under such circumstances, besides efforts on the continued monitoring of glaciers included in the network of the WGMS, short-term goals should include efforts to restore observations on the Abramov glacier (Pamir-Alay), the Kara-Batkak and Golubin glaciers (Tien Shan) and the implementation of similar observations on additional glaciers in Tibet, the Himalayas, the Pamir, and the Karakorum in particular. Additionally, it would be useful to create a coordinated network of test glacier basins, where glacier hydro-climatic observations are carried out in accordance within a coordinated programme. Another important goal should be an effort to organize the compilation of a glacier inventory. Only on its basis, an objective comparative analysis of glacier system dynamics could be made and well-founded estimations of the mountain glaciation in Asia could be done. Good prospects for creating a global glacier inventory based on remote sensing techniques can be seen within the framework of the GLIMS programme. At present, repeated glacier inventories are available only for the mountain regions of Pamir, Gissar-Alay, and Tien Shan within the territory of the former USSR. During last decades (since 1970), glacier inventories of some basins of the Himalaya and the Karakorum have also been compiled (Tsvetkov et al. 1998). The work on the second glacier catalogue of China is also finished. To improve the efficiency of this work, the specialists should coordinate their efforts and agree on the contents of the catalogues and methods of observation.

Recent glaciation changes of the high mountains of Asia

Although the total glacier area on the Northern slope of the Zailiyskiy Alatau and Shelek river basins decreased during the period of 1956 to 1975, 31 % of the 369 glaciers within those basins were advancing. The total areal increase of these glaciers during this period reached 15.7 km². During the period from 1975 to 1990, the rate of glaciers with a positive mass balance decreased by 2.4 %. Similar dynamics were observed in other areas (Takeuchi et al. 2006). From 1943 to 1977, seven glaciers (4 %) advanced in the Akshirak massif, and the surface height in the ablation zone increased on 32 glaciers (18 %). However, during the subsequent period all glaciers were retreating (Aizen et al. 2006). A similar picture was observed in mountains of China (Yao Tandong et al. 2007). According to data of the WGMS, the simultaneous presence of receding and advancing glaciers in the 1960s – 70s was characteristic for continental mountain-glacial systems of the world and by the end of the 1970s the quantity of advancing and receding glaciers was practically even with about 45 % of observed glaciers in the Northern hemisphere having positive mass balances in the period from 1960 to the 1980s.

The degradation of glaciation in Central Asia varies in time and by region. The rate of reduction of glacier area in the Akshirak glacier massif in Central Tien Shan changed from 0.12 %/year during the period 1943 – 1977 to 0.33 %/year during the period 1977 – 2003 (Aizen et al. 2006). In the mountains of Asia, the lowest rates of area reduction (0,01 – 0,06 %/year) in the last decades of the 20st century were observed on the Tibetan plateau (Xin Li et al. 2007), while maximum values (0.80 – 0.83 %/year) were found in the northern periphery of the Tien Shan (Aizen et al. 2006; Severskiy et al. 2006). These differences can be attributed to the fact, that in the southeast Tibetan plateau the intensity of solar radiation in the ablation zone is only 1/6 of the theoretically possible, and condensation exceeds evaporation resulting in low degree day factors of only 3.2 ($cm/K^{-1}d^{-1}$), whereas in Central Tien Shan this value exceeds 12.5 $cm/K^{-1}d^{-1}$ (Aizen & Aizen 1997a,b). Comparisons of glacier mass balances from different regions of Asia are given in figure 3, while figure 4 compares cumulative mass balance series from around the globe.

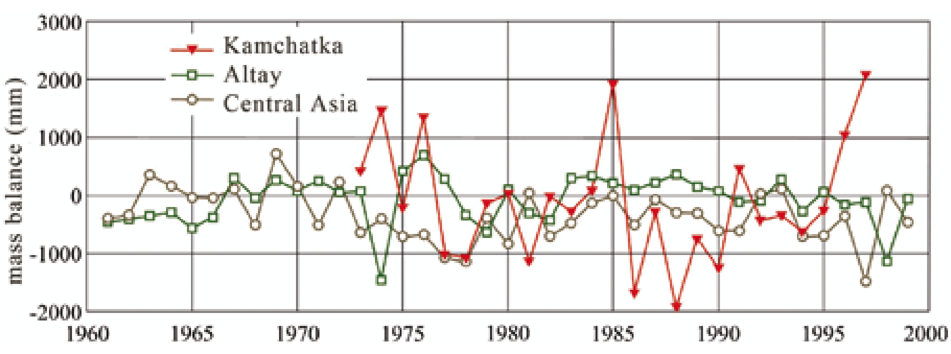

Figure 3
Range of annual mass balance of glaciers in Asia (Dyurgerov 2005)

It should be noted, that in comparison to Central Asia the glaciers of the Altay were generally characterized by a stronger stability; during 1966 – 1973, 1975 – 1977, 1983 – 1990 and 1993 their annual mass balance was actually positive, although the cumulative mass balance over the entire period remained slightly negative (Figure 4). Starting from the end of the 1980s – beginning of the 1990s, the rates of glacier retreat in many parts of the world increased greatly (Haeberli 2005; Dyurgerov 2005). This increase was caused by abnormally high average temperatures in this period and corresponds well with changes of sea ice and the areal reduction of seasonal snow covers in the Northern hemisphere at the rate of 0.2 %/year (Dyurgerov & Meier 2005). The rate of glaciation wastage in Central Asia is one of the most intense in the world (Figure 4).

Another important field of research is the assessment of the contribution of mountain- and subpolar glacier wastage to sea level rise. The global mass balance of glaciers can be transformed into units of sea level change: a 361 km³ water equivalent corresponds to a sea level rise of 1 mm (Climate change 2001; Dyurgerov 2005; IPCC 2001). According to Dyurgerov (2002, 2005) the global annual mass balance changed from 82 mm/year (–56 km³/year) for the period of 1961 – 1976 to 125 mm/year (–85 km³/year) for the period of 1977 – 1987 and to 217 mm/year (–147 km³/year) for the period of 1988 – 1998. This suggests a considerable increase in the rates of glacier retreat during the last decade of the 21st century on a global scale. The increase in the retreat rates during the 1980s to the beginning of the 1990s was so significant, that the homogeneity of the data is being questioned as well as their suitability to estimate short-term glaciation dynamics (Dyurgerov 2005). In a number of mountainous glacier regions (Caucasus, Altay, Scandinavia), however, this shift is not seen and the curves of cumulative mass balance in the 1980s to the beginning of the 1990s show a reverse development compared to most glacier regions in other parts of the globe.

The presented results (Figures 3 and 4) show glacier changes calculated as average for large territories with large mountainous glacier regions (Alps, Caucasus, Altay) to the sub-continent scale (high peaks of Asia). However, the character of glacier changes of individual glacier systems can differ considerably from the average conditions over large territories. Besides, even

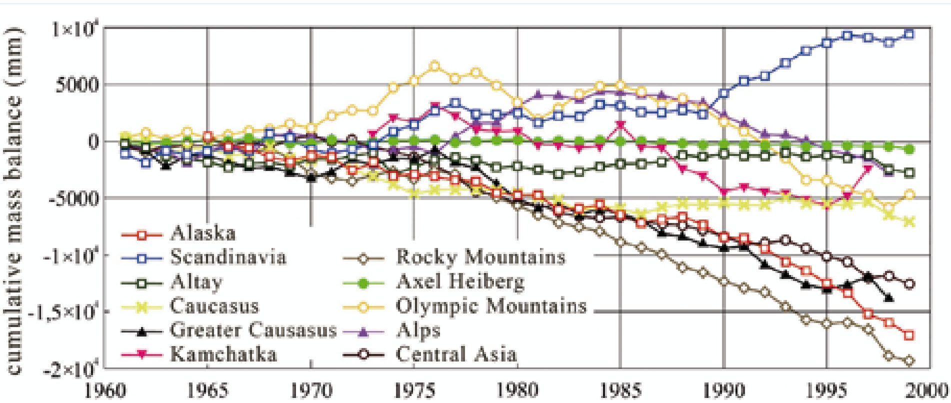

Figure 4
Long-term trends in the cumulative mass balance of glaciers in various regions of the world (Dyurgerov 2005)

within individual glacier systems, the rates of these changes can vary depending on relief, orography, orientation, and location of the region. These peculiarities are analyzed in the following for the mountain glaciation of Central Asia. The most detailed data for the analysis of glaciation dynamics in the region is available for the mountainous territory of South-Eastern Kazakhstan, the Northern Tien Shan and the Dzhunghar Alatau. Since 1958, glaciological, climatological, and hydrological observations were carried out at the Tuyuksu glacier station by the Institute of Geography of the Ministry of Education and Science of the Republic of Kazakhstan. If we include historical sources and evidence, the period of observation exceeds 125 years. Besides, airborne and satellite imagery of mountains in South-Eastern Kazakhstan used to compile standardized glacier inventories are available for Dzhunghar and Zailiyskiy-Kungey glacier systems, respectively (1955 – 1956 and 1999 – 2000). The data of Tuyuksu glacier mass balance monitoring (Figure 5) and a comparative analysis with glacier catalogues data indicate, that glacier changes in this region correlate well with the typical behavior of glaciers in the mountains of Central Asia (Figure 4). As in most glacier regions of the world, the glaciers were in a more or less stable state until the end of the 1970s. An increased retreat started in the beginning of the 1970s when unusually high air temperatures were observed during a number of consecutive years. Similar changes were observed at the Shumskyof glacier in the Dzungarian Alatau, the Abramov glacier in Gissar-Alay, the Kara-Batkak glacier in Terskey Alatau and the Golubina glacier in Kyrgyz Alatau. An abrupt acceleration of glacier retreat from the middle of 1980s on as mentioned

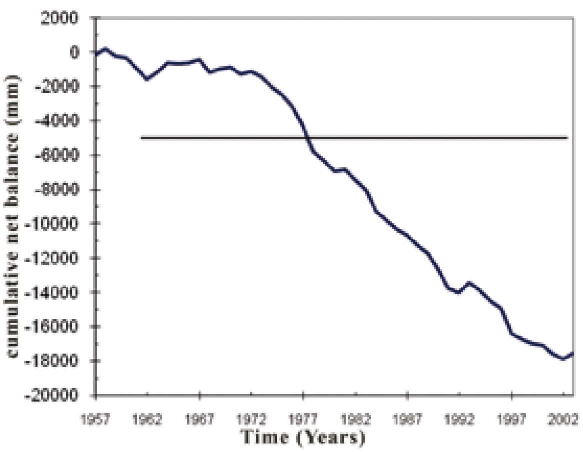

Figure 5 *Cumulative mass balance of Central Tuyuksu glacier for the period 1957 – 2005*

above could not be observed on the Tuyuksu glacier. On the contrary, the mass losses on Tuyuksu decreased starting at the end of the 1980s (Figure 6). A similar progression was seen for the Zailiskiy, Kungey and Dzunghar Alatau (Severskiy et al., 2006).

This type of glacier behavior corresponds well with studies about the glaciation for all of the high mountain regions of Asia (Dyurgerov & Meier 2006); after a sharp acceleration of mass losses from the early 1970s until 1977 – 1978 the process stabilized, and by the beginning of 1990s it had slowed down considerably. However, subsequently mass losses have increased again. Such a regime corresponds quite closely to features of global warming: whereas up to the end of the 1980s air temperature trends at different latitudes of the Northern and Southern hemispheres had different signs, they were almost exclusively positive in all latitude zones of the Earth, especially in the Northern hemisphere, from the end of the 1980s on (Dyurgerov & Meier 2006). A considerable slowdown in the glacier retreat rates from the beginning of the 1980s on was observed in three basins of the Gissar-Alay (Batyrov and Yakovlev, 2004) as well as on three glaciers in China (Glacier No. 1 in Eastern Tien Shan, Maly Tongkemali glacier in the Tanggula mountains and Meikuang glacier in the Kunlun Shan.Yao). Tandong et al. (2007) and Glazyrin (2007) estimated that the deglaciation rates in the Gissar-Alay accelerated by almost 20 % after 1980 in comparison with an average for the period between 1957 and 1980 (from 0.68 to 0.80 %/year). Glazyrin (2007), however, also estimates that the Pamir glaciers retreat rates for the period of 1980 – 2005 have slightly decreased, from 0.54 %/year in 1961 – 1980 to 0.50 %/year in 1980 – 2005, while some acceleration in the rates was observed in the Central Tien Shan (Kuzmichenok 2007). These discrepancies could be explained in part by errors in the method of deriving volume changes from air photographs.

As mentioned, glacier retreat rates can deviate even within a glacier system depending on the location of the region in the mountain system, on the predominant orientation of the mountain range (macro-slope), as well as on the altitude and orientation of the glacier itself. For example, in the Zailiyskiy-Kungey glacier system the maximum rate of areal retreat from 1955 – 1999 (0.96 %/year) was observed on the southern slope of the Kungey Alatau (Chon-Aksu river basin), while the minimum (0.49 %/year) was detected in the Chon-Kemin river basin situated nearby.

In the Dzhunghar glacier system the maximum rate of glacier retreat (1.08 %/year for 1956 – 1990) can be found on the southern slope of the mountains, whereas in the nearby basin of the Koksu river it is 20 % less, and the minimum (0.72 %/year) was observed in the orographically closed basins of the rivers Tentek and Yrgayty at the western periphery of the Dzhunghar Alatau (Severskiy et al. 2006). Considerable inter-basin deviations in the glacier retreat rates are also reported from other glacier systems of Central Asia (Table 2).

The data presented in table 2 are taken from the Catalogue of Glaciers (1976). It is difficult to explain the glacier retreat rates (up to 2.6 %/year) and their regional deviations in the basins of the tributaries of the Syrdarya river. Also unclear are the causes of the very small glacier retreat rates in the tributaries of the Pyanj river below the Vanch river estuary (0.32 %/year) and in the Muksu basin (0.27 %/year). They may be explained by the fact that these are the most heavily glacierized basins and the large ice masses have a cooling effect on the local climate. In order to understand regional discrepancies in glacier retreat, it is important to be aware that the rise of global air temperatures influences glaciers indirectly through many factors and processes, such as changes in the general circulation of atmosphere, cloud cover, solar radiation, and local sensible heat fluxes (Aizen & Aizen 1997a, b). Furthermore, it is also necessary to recognize, that glacier behavior also depends heavily on the accumulation processes from solid precipitation. The differences in these processes are especially great in regions like Central Asia with little or moderate overall snowfall. Depending on the orientation of the basin and other topographical features, the range of maximum snow accumulation at comparable heights even in nearby basins can differ substantially often by several times of magnitude (Severskiy 1982; Severskiy and Xie Zichu; 2000, Severskiy & Severskiy 1990).

As mentioned, another peculiarity is that the regime of each glacier is unique and can differ not only from the average values for this type of glacier system, but also from those of a nearby glacier. The causes of these deviations lie in the influence of the large variability in local factors – from orographic peculiarities and relief to the morphological type of the glacier and slope exposition (Kotlyakov 2004; Krenke 1982). The degree of influence of local factors on the main glaciological characteristics depends much on the size of the glacier itself (Severskiy 1982; Severskiy & Severskiy 1990; Severskiy 1997): the bigger the glacier is, the smaller is the influence of local factors.

Table 2 Long-term changes of glacier area Fgl (km²) in Central Asia (source: Agaltseva & Konovalov 2005)

Basin/Region	Year	F_{gl}	Year	F_{gl}	Retreat of glacier, km²	Rate of retreat, %/yr	Duration of period, years
West Tien Shan	1957	170.8	1980	146.8	24.0	0.61	23
Vanch	1957	344.8	1980	291.6	53.2	0.67	23
Gunt	1957	534.1	1980	441.1	94.0	0.76	23
Matcha	1957	506.0	1980	437.9	68.1	0.58	23
W. Kzyl Su	1966	527.3	1980	486.4	40.9	0.55	14
Muksu	1966	2064.8	1980	1987.5	77.3	0.27	14
Obihingou	1957	810.2	1980	705.1	105.1	0.56	23
Pyanj (1)	1957	383.7	1980	268.9	114.8	1.30	23
Pyanj (2)	1957	52.0	1980	48.1	3.9	0.32	23
Syrdarya (1)	1964	548.1	1980	449.6	98.5	1.12	16
Syrdarya (2)	1964	303.9	1980	180.1	123.8	2.55	16
Shahdara	1957	216.3	1980	166.7	49.6	1.00	23
Yazgulem	1954	330.4	1980	262.7	67. 7	0.79	26
Total		**6793.4**		**5872.5**	**920.9**	**0.65**	

Notes: Pyanj (1) – RH tributaries of the Pyanj above Gunt estuary, Pyanj (2) – RH tributaries of the Pyanj below Vanch estuary, Syrdarya (1) – LH tributaries from the Aksu estuary and further below, Syrdarya (2) – LH tributaries of the Syrdarya from Karadarya estuary to Aksu estuary.

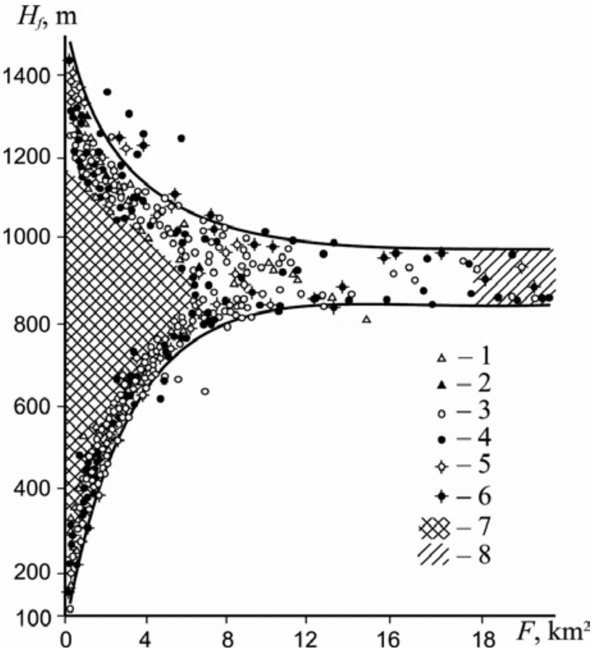

Figure 6 *Dependence of firn line Hf on glacier area F. 1–Altay, Sayany; 2–Dzhungar Alatau; 3–Tien Shan; 4–Pamir, Gissar-Alay; 5–Big Caucasus; 6–Alps; 7–continuous stretch of dots; 8–zone where the glacier space is shown out of scale (F>>20 km²).*

Thus, it was defined that for all the mountain glaciers the dependence of the firn line altitude (Hf) on glacier area (F) is not variable: with an increase of the glacier size the range of deviations in the firn line altitude in the region quickly decreases and from a certain threshold on it is constant (Figure 6).

As shown in figure 6, the interdependence Hf = f (F) has an asymptotic character: at $F \geq 14\,km^2$ a further increase in glacier area does not affect the altitude of the firn line. Since the position of the firn line on big glaciers is less influenced by local non-climatic factors, the signal of macroclimatic conditions becomes more apparent.

Analysis of revised data from the Catalogue of Glaciers (1976) on Zailiyskiy-,Kungey- and Dzhunghar-Alatau glaciers show that:

- It cannot be stated that smaller glaciers retreat faster than large ones. In spite of margin melt effects and depending on local conditions their retreat rate can be larger or smaller than that of large glaciers.
- The influence of local factors on glacier retreat rates depends to a great extent on its size. A glacier area of 13 – 14 km² seems to be a threshold value: if it is exceeded, the self-regulation mechanism of the glacier is so strong that it neutralizes all local factors and its regime is defined by macroclimatic conditions of the region alone. Such glaciers are of the biggest interest for studying the connection between glaciation and climate.
- The regime of each glacier is unique and can differ substantially from that of a nearby glacier. Thus, glacier regime data referring to one glacier can hardly be applied to others, even if they are located close to each other. The differences can be very significant or even have a different sign.
- Territorial differences in the retreat rates are defined by the dominating aspect of slopes and the prevailing direction of the movement of humid air masses, as well as on the location of the region in the overall mountain system. In Kazakhstan and Central Asian countries, maximum rates of retreat appear on southern slopes, minimum values can be found in valleys, in orographically closed basins of the East and in humid basins on the western periphery of the mountains, which have a favorable location in respect to the prevailing direction of moisture movement. In the first case the key role is attributed to a comparatively high relevance of air temperatures on southern slopes. In the latter two cases the reason for the moderate retreat is found in a larger share of summer precipitation in its annual total: frequent summer precipitation, the major part of which still falling in solid form over glaciers, is favorable for glacier preservation.

Impact of Glacier Retreat on Runoff

The term "glacier runoff" is treated in this paper as runoff of melt water from seasonal snow, firn, and ice, as well as liquid precipitation running into the river network from the surface of the glacier (Kotlyakov 1998). Most scientific publications support the opinion that glacier runoff must increase with glacier retreat due to global warming. One of the most recent summaries on this issue was compiled by Kotlyakov (2004). The goal was to calculate only the part of glacier runoff which constitutes additional runoff due to glacial retreat in comparison to runoff from a glacier with a stable mass balance. The calculation of this "runoff of degradation" is based on the use of observational data on mass balance changes of a glacier which is retreating as a result of climate warming (Figure 7) (Kotlyakov 2004).

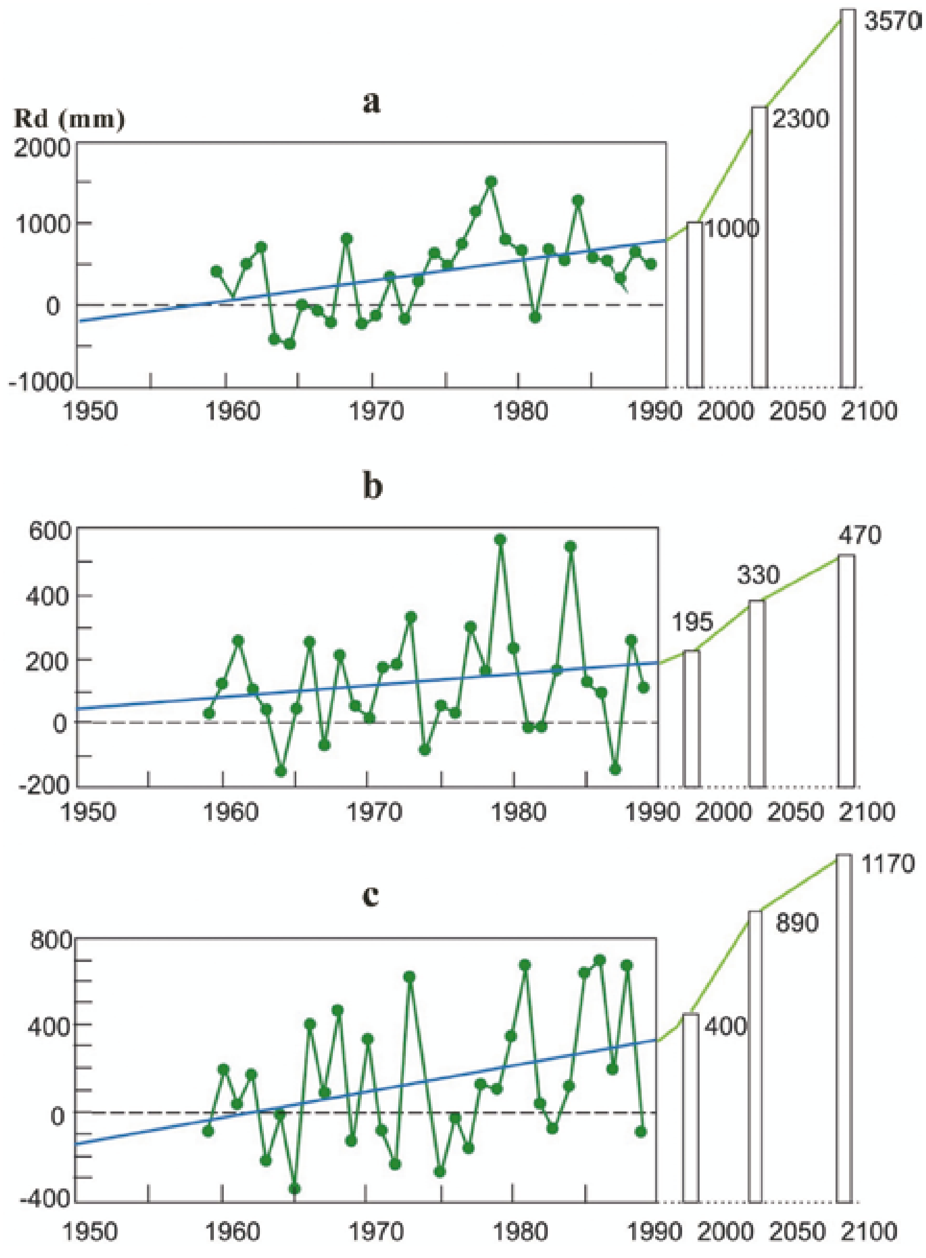

Figure 7
Present trends in "runoff of degradation", Rd, and estimated future values extrapolating this trend calculated for the glaciers Tuyuksu (a), Sary-Tor (b) and Glacier No. 1 (c).

Similar trends in "runoff of degradation" were observed by monitoring six glaciers in Norway, representing glaciation in maritime climate (Kotlyakov 2004). Extrapolating the existing trend in air temperature monitored at the stations of the Tien Shan into the future, Kotlyakov (2004) suggests that by 2100 the average annual temperatures in Central Asia will rise by 1.5 °C and by 2350 by 4.5 °C. The volume of runoff by 2100 will increase by 3.3 times compared to 1975, but afterwards, due to the fast reduction of glacier areas, it will start to decline. The changes in maritime type glaciers can lead to their retreat, possibly to disappearance, which in turn will cause a comparatively fast increase of sea level (5 – 7 m per decade). Mountain glaciation of moderate latitudes will shift into extremely negative mass balances (up to –3, –5 m/year) or will disappear completely. The runoff volume of mountain rivers will decrease greatly (due to the loss of glacier resources) which will have negative consequences for agriculture (Kotlyakov 2004).

The data suggest that in Central Asia the turning point, where the runoff reducing effects of glacier areal decrease outweigh the runoff increasing enhanced glacial melt, was reached a long time ago. At present, the dominant process seems to be a continuous decrease of glacier runoff with climate warming. For example, runoff from the Tuyuksu glacier (Northern Tien Shan) decreased for the last decades due to the decrease of its extent (Vilesov & Uvarov 2001). A similar development of glacial runoff change was revealed in the Zeravshan and Vakhsh river basins (Kotlyakov 2006) as well as in the Dzhunghar Alatau (Vilesov & Morozova, 2004). Under such circumstances it seems strange that the long-term runoff of the main rivers in Central Asia, including the Amudarya, Syrdarya and Ili, at least, remained stable over the last 50 years (Glazyrin 2007; Chub 2000; Aizen et al. 1997; Severskiy et al. 2006). During the same period, in spite of a significant decrease of annual snow accumulation on the glaciers of Tien Shan (e.g. Kotlyakov 2004), mean precipitation values and maximum snow water equivalents remained stable (Pimankina 1998, 2000; Blagoveshchenskiy & Pimankin 1997; Artemeva & Tsarev 2003; Braun & Hagg 2007; Severskiy et al., 2006). During this period, the seasonal runoff distribution did not change either (Galperin 2003). These observations indicate the presence of a certain compensation mechanism. It is suggested that this mechanism could be a compensating increase of melt water runoff from permafrost and buried ice. For the period from 1958 to 1998, the share of melt from buried ice at the Tuyuksu glacier reached about 20% of total runoff from the open part of the glacier. In the Zailiyskiy glacier system (Northern slope of Zailiyskiy Alatau and Shiliek river basins) the fraction of open ice areas in total area was reduced to 13.6% from 1955 to 1990. Consequently, the contribution to runoff from buried ice must have increased accordingly.

It is estimated that the reserves of underground ice in the high altitudes of Central Asia and Kazakhstan are equivalent to the present glacier ice resources (Gorbunov & Severskiy 2001). In the mountains of China they are considered to be twice as high as the present glacier ice volume (Singh 2007; Xin Li et al. 2007). Taking into consideration that the melt rates of underground ice are much lower than those of glaciers, it is assumed that even if the present trend of climate warming continues, the impact of the mentioned compensation mechanism can stretch over hundreds of years. It should further be noted that a significant decrease of water resources caused by glacier retreat is unlikely in Central Asia due to the fact that the key source of glacier (and total) runoff formation is the melting of seasonal snow covers. This leaves us to hope that the continued degradation of glaciation will not lead to a significant decrease in total runoff and in regional water resources, at least for the next decades. Naturally, this optimistic point of view needs to be justified through complex, well aimed research projects coordinated at international and regional levels. In this respect, geocryological research, thermal regime monitoring of seasonal and perennial permafrost, as well as the perfection of assessment methods to quantify underground ice reserves should be carried out. The time has come when buried ice and perennial permafrost reserves should be viewed not only as the indicator of climatic change and an unfavorable factor for the economic development of high altitudes, but also as strategic resources of runoff formation.

Conclusions

The data of the World Glacier Monitoring Service and corresponding scientific publications leave no doubt that the glaciation of the Earth has been degrading since the middle of 19th century. Especially intensive degradation in many areas was observed in the beginning of the 1970s, with another increase in degradation rates in the mid-1990s.

The response of glaciers to climate changes is shown in fluctuations of their mass balances. Therefore, monitoring of glacier mass balances is crucial for the estimation of modern glaciation and its possible influence on the environment and water resources. At the same time the regime of an individual glacier cannot be assumed to be representative for the changes of a whole glacier system or the glacier within a larger region. With this in mind, further efforts on standardi-zed glacier inventories should be made. Only the comparative analysis of consecutive glacier inventories allows the accurate quantification of ice resource changes of complete glacial systems as a reaction to climate change and an analysis of the laws and reasons of territorial differences of glaciation dynamics. The existing network of regular glacier monitoring in Asia is obviously not adequate to assess changes in glaciation and their possible influence on regional water resources. At the moment there are only 18 glaciers on which the duration of annual glacier mass balance measurements has exceeded 20 years.

On 11 of them observations stopped in the 1980s – 90s and presently, only three glaciers in the Altay, two glaciers in the Tien Shan and two glaciers in the Caucasus have ongoing observations.

The laws of distribution and regimes of snow covers of high-mountainous areas (above 3000 m), where more than 50 % of snow resources in the zone of runoff formation of the main rivers of Central Asia are concentrated, are the most poorly studied. The monitoring of snow cover with field techniques and with remote sensing approaches deserves special attention in this context. Taking into account the increased role of underground ice as strategic resource of fresh water, it is necessary to strengthen the research on the reaction of permafrost to climate change.

The successful solution of the mentioned problems is probably only possible through well coordinated studies and a close cooperation of scientists of different countries. For this purpose, it would be very useful to create a network amongst the countries of Eurasia to apply and standardize monitoring methods and to create regional databases and information systems. For such cooperation it would be desirable to create a Regional Glaciological Centre under the aegis of UNESCO with a scientific council composed of members of the countries of Eurasia.

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Recommendations by the Conference

Background and scope

The papers published in this volume deal with the role of snow and ice resources in the Central Asian high mountains as sources of water supply and origin of catastrophic floods. While most of the papers concentrate on the river systems of Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan, several papers focus on the river systems of China, Pakistan, India and Nepal, emanating from the Himalaya, Karakoram, Pamir, Tien Shan and the mountains of the Tibetan plateau.

Some of the rivers in this region, particularly the Indus, the Huang He and the drainages of the Aral Sea and Lake Balkhash, are heavily dependent on snow and glacier melt in their mountain headwaters, with few additional precipitation inputs in the rivers' lower reaches. The higher and lower levels of other major river basins in the region, including the Yangtze, Mekong, Salween, Ganges and Brahmaputra, are fed by significant meltwaters from the high mountains and abundant rainfall in the monsoon season and are hence less dependent on snow and ice melt.

It has now been generally recognized that global warming is affecting the whole region. With rising temperatures glaciers and permafrost melt-water held in semi-permanent storage is released into river systems in addition to annual precipitation. However, the eventual disappearance of glaciers and permafrost will finally reduce discharges. It is therefore pertinent to ask how long these additional meltwaters will be available. Rising temperatures effectively lengthen summers and shorten winters; a smaller proportion of precipitation falls as snow and a larger proportion as rain with consequent effect on river flow regimes.

However, there are major uncertainties concerning long-term precipitation trends and so caution must be exercised when developing long-term predictions of river flows. Not only are there changes in the quantities of water available and in flow regimes, but there is an increased likelihood of catastrophic floods from glacier lake outbursts and subglacial lakes (jokulhlaups).

The interplay between changes in the cryosphere and river regimes is not only of scientific interest. It is of crucial importance to the lives and livelihoods as well as to the economic and social development of more than 1 billion people living in the affected river basins. As human population expands and economic activities multiply, water demand increases and the numbers of people vulnerable to floods increases. Understanding hydrological systems and the way how river regimes change over time is of vital importance to water managers and to all those depending on water.

Therefore, the case can be made that it is necessary to assess and monitor all aspects of water resources in the highly important headwaters of the Central Asian rivers and, in particular, to monitor the impacts of melting snow, glacier ice, and permafrost on river regimes.

The recommendations

Building on existing research sites, a regional network of benchmark basins and hydro-meteorological measurement sites should be developed to provide an efficient long-term capability to assess and monitor changes in snow, glacier and permafrost conditions affecting river regimes and impacting on water-related disasters.

Ongoing studies on the hydrological impacts of glaciers, snow and permafrost should be reviewed and, based on the findings, further research needs should be formulated.

A regional cryospheric research centre should be established in Central Asia to promote international cooperation required in setting up the regional network of monitoring sites. The activities and operation of this centre should be linked to other global and regional centres already existing, such as the World Glaciology Data Centres.

An advisory board including scientists and experts in economic and social development should be set up to oversee the development of these activities. Support for these activities should be sought from agencies such as the Global Environmental Facility, the World Bank, the Asian Development Bank, other relevant UN agencies and professional organizations.

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Shrinkage of summer-accumulation – glaciers in Asia under consideration of downstream population

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Recent glacial retreat in High Asia in China and its impact on water resources in Northwest China

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Present and future impact of snow cover and glaciers on runoff from mountain regions – comparison between Alps and Tien Shan

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Current and projected changes of glaciation in Central Asia and their probable impact on water resources

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Distribution and changes of glacier, snow and permafrost in China

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Changes in the extent of glaciers in the Russian Altay in the second half of the 20th century

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Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions

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Ground ice and icings in Central Asia: geography and dynamics

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State of cryolitogen thickness of North Tien Shan

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Glaciers of Central Asia: current situation, changes and possible impact on water resources

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Abbreviations

CAREC	Regional Environmental Centre for Central Asia
DSS	Decision support system
FAO	Food and Agriculture Organization
FRIEND	Flow Regimes from International Experimental and Network Data
GEF	Global Environment Facility
GLOWA	Global Change and the Hydrological Cycle
GWP	Global Water Partnership
GWSP	Global Water System Project
HELP	Hydrology for Environment, Life and Policy
HWRP	Hydrology and Water Resources Programme of WMO
ICIMOD	International Centre for Integrated Mountain Development
IHP	International Hydrology Programme of UNESCO
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resource Management
UN	United Nations
UNEP	United Nations Environment Programme
UNESCAP	United Nations Economic Commission for Asia and the Pacific
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization
WMO	World Meteorological Organization
WWAP	World Water Assessment Programme
WWDR	World Water Development Report

Web Sites

UNICEF Childinfo: Monitoring the Situation of Children and Women
www.childinfo.org

Food and Agriculture Organization of the United Nations
www.fao.org

Global Environment Monitoring System/Water
www.gemswater.org

Global International Waters Assessment
www.unep.org/dewa/giwa/

United Nations Development Programme
www.undp.org

UNESCO's Man and the Biosphere Programme (MAB)
www.unesco.org/mab

UNESCO Water Portal
www.unesco.org/water

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www.unhabitat.org

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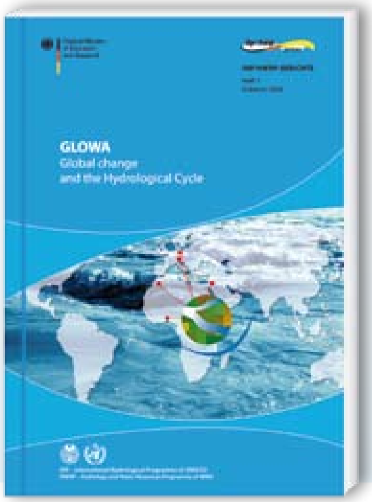

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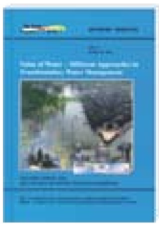

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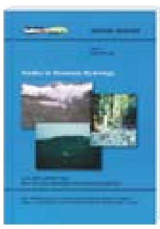

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