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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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Abstract

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 (Fig. 1).

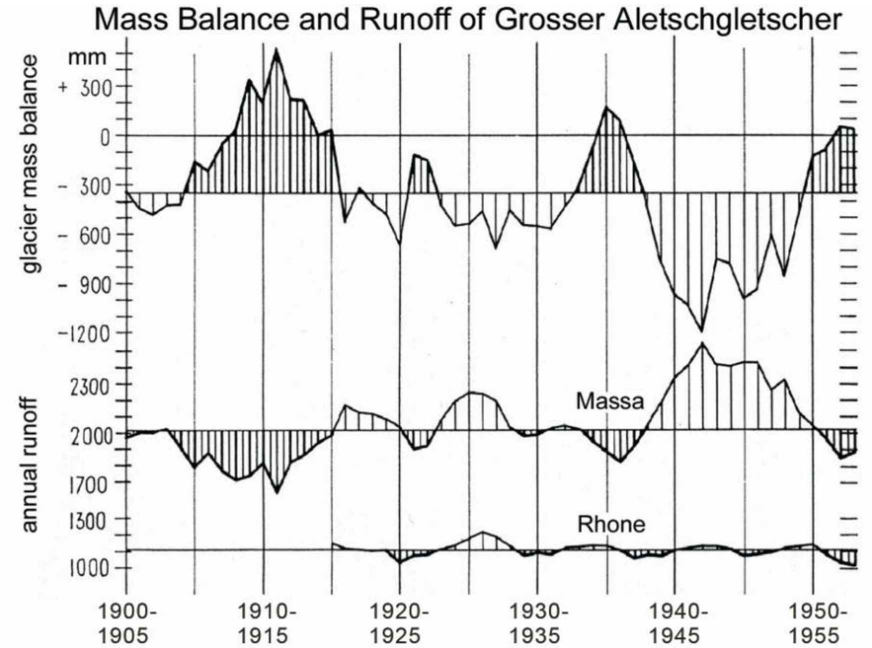

Fig.1. Mass balance and runoff of Grosser Aletschgletscher, Switzerland (Kasser 1959, slightly changed). 5-years running mean.

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 Aletsch Gletscher 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.

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 (Fig. 2).

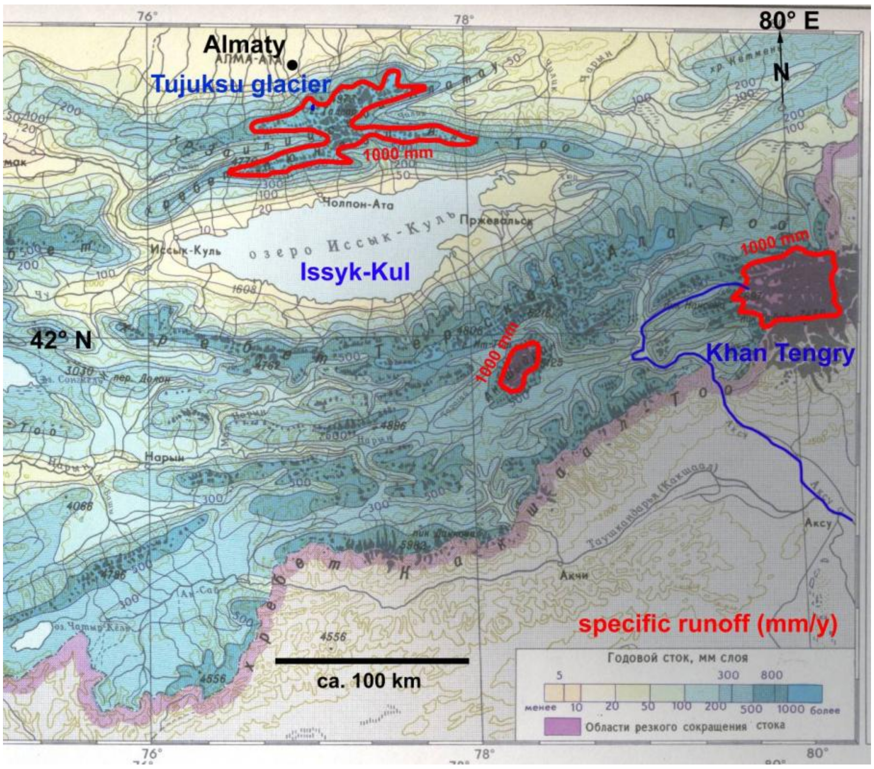

Fig. 2.: Specific runoff in the Tien Shan mountains, source: Kotlyakov et al. (1997).

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.

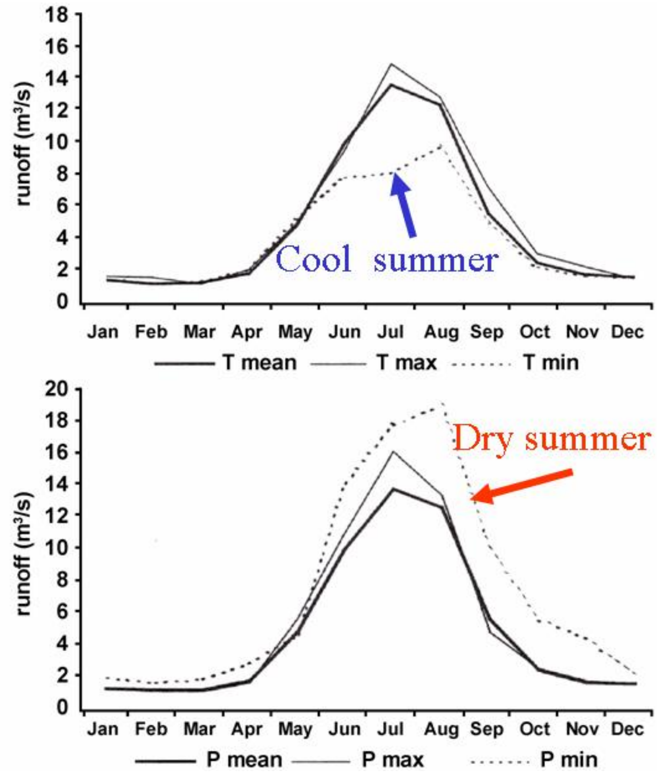

Fig. 3: Compensation effect of glacial discharge, Chon-Kyzylsu basin, glacierization 29%, Terskey Ala-Too Range (Dikich & Hagg, 2004).

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 (Fig. 4).

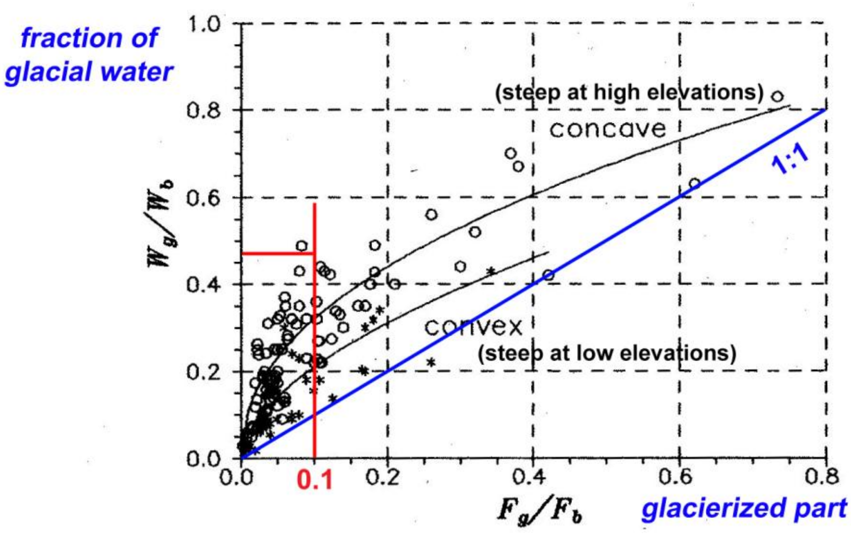

Fig. 4: The relationship between the part of glacial water (Wg) in the total annual river runoff (Wb) and the glaciation of river basin (Fg/Fb) when the hypsometric curves are convex (stars) and concave (circles). Taken from Glazirin (1996).

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.

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.

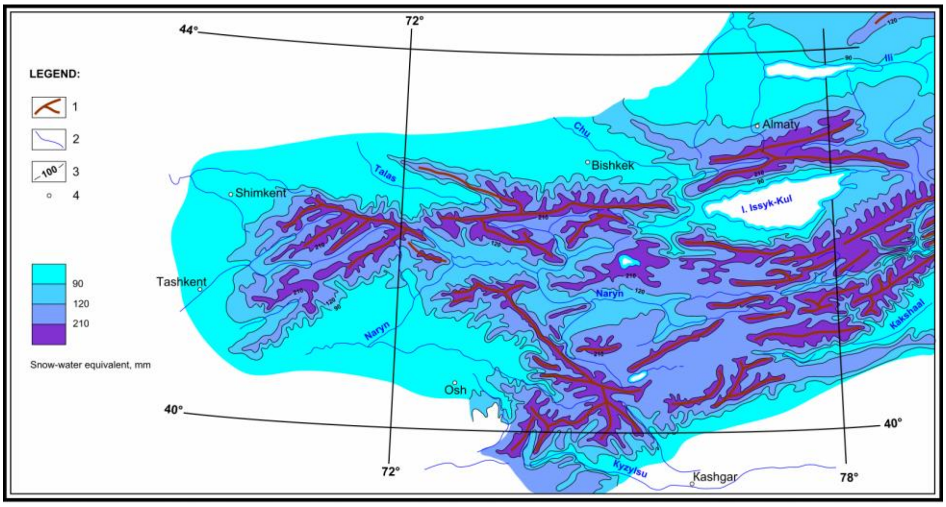

Figure 5: Snow-water equivalent in the Tien Shan, taken from Schröder and Severskiy (2002).

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.

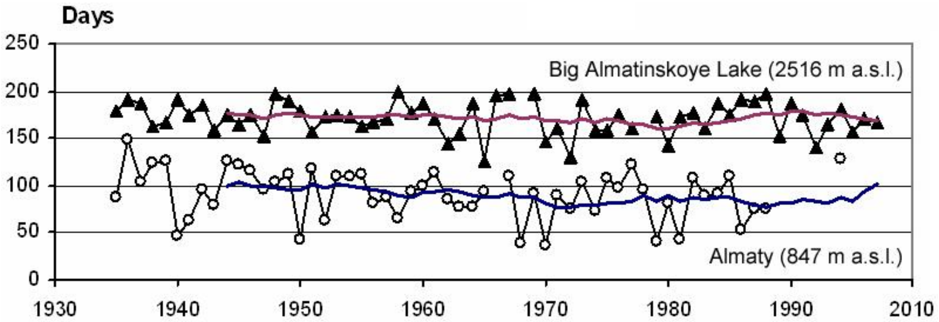

Fig. 6: Duration of snow cover. Based on Pimankina, taken from Schröder and Severskiy (2002)

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).

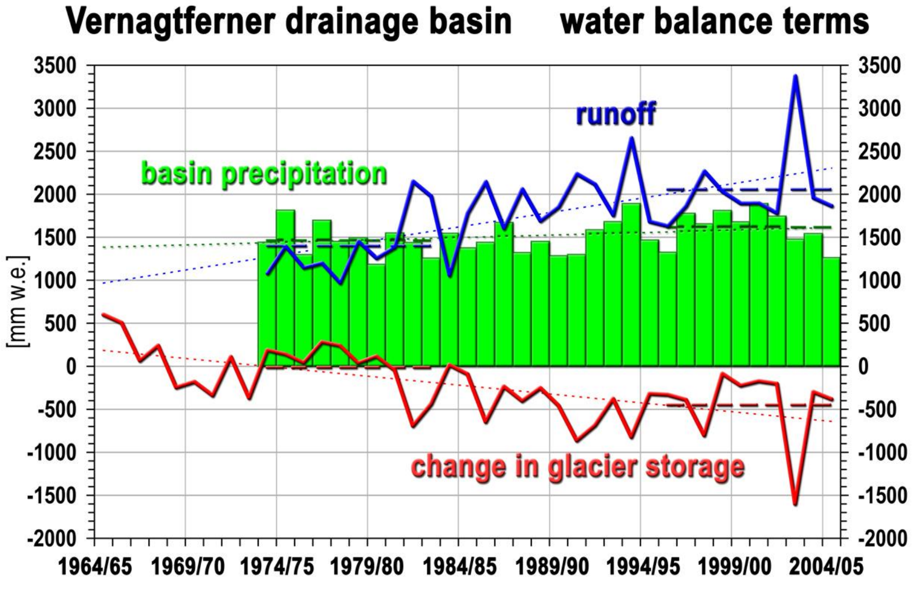

Fig. 7: Water balance of Vernagtferner basin. Evaporation was derived externally and is in the order of 120 mm/y.

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 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).

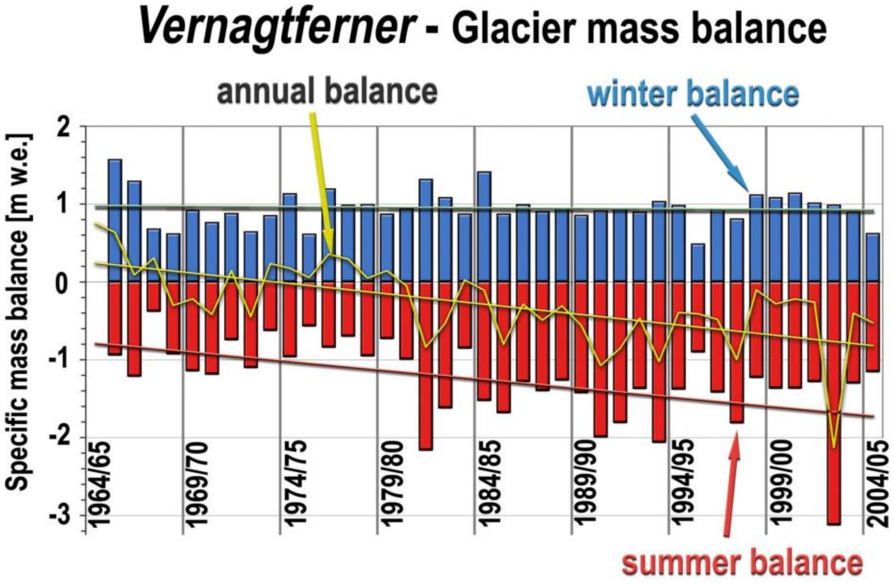

Fig. 8. Glacier mass balance of Vernagtferner.

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 %.

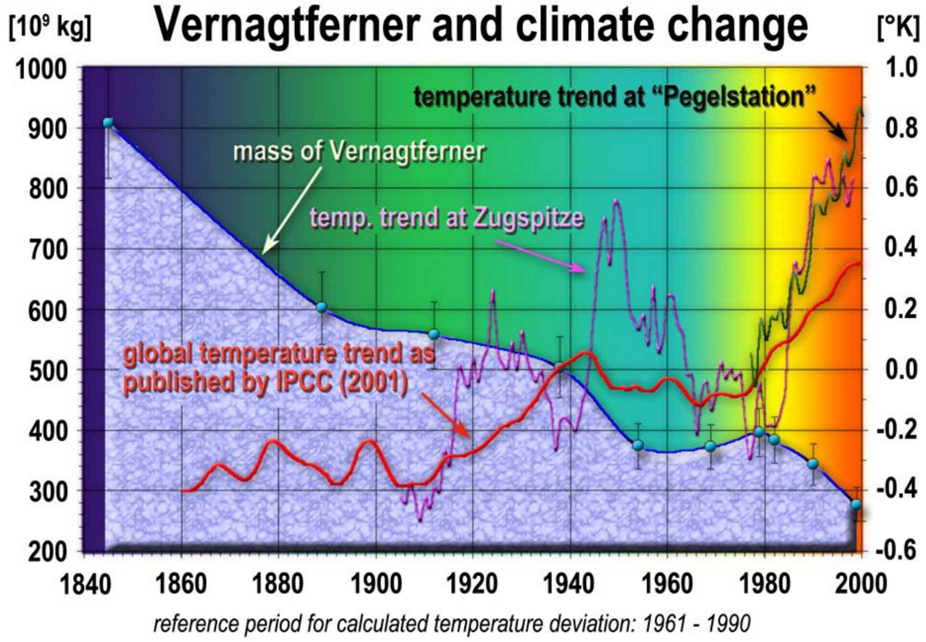

Fig. 9: The mass loss of Vernagtferner against the background of global and local temperature curves.

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).

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 (km^2)	18.0	-4.2 %	35.2	-8.7 %
Change in Height (m)	8.3		15.1	
Change in Volume (km^3)	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	

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.

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).

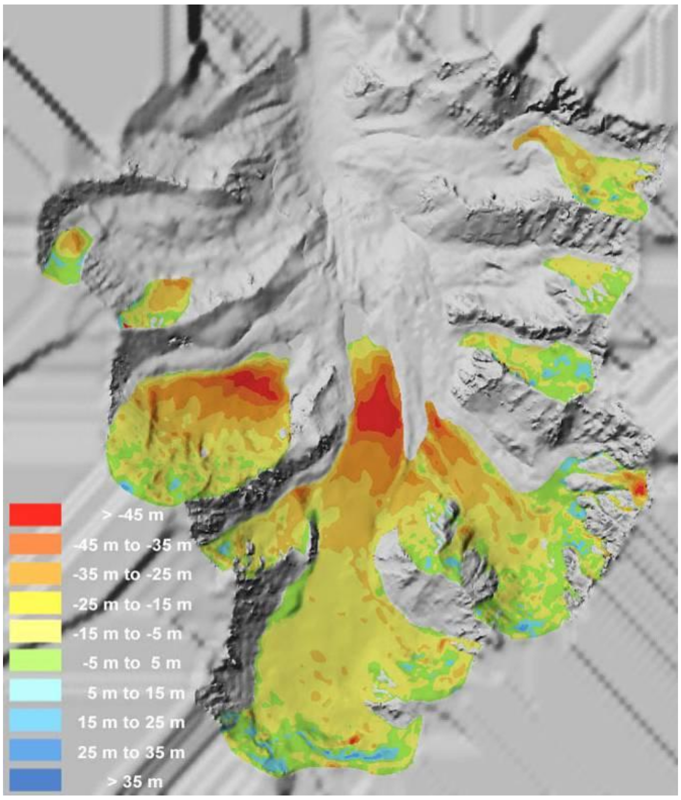

Fig. 10: Height differences of Tuyuksu glaciers 1958-1998.

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.

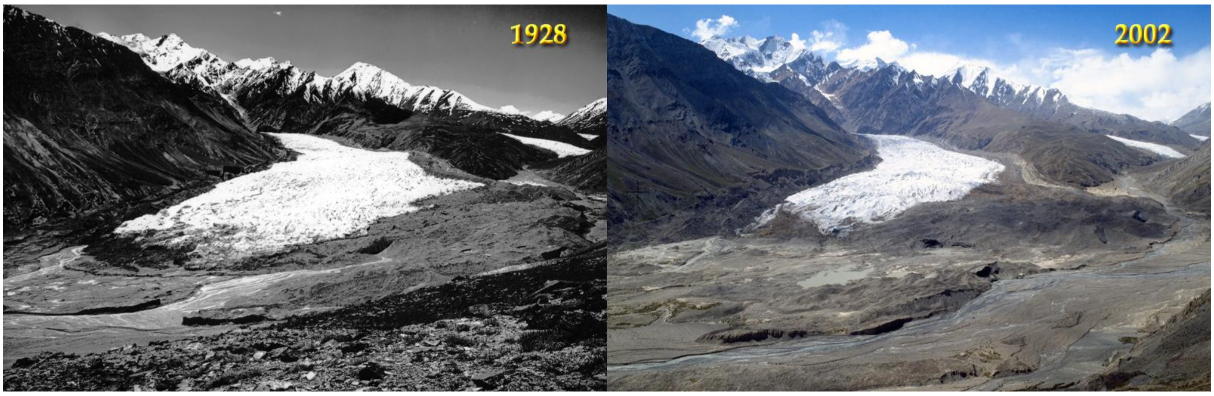

Fig. 11: Tongue of Muskulak glacier 1920 and 2002, taken from the same location.

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 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 (Fig. 12). To cover the whole range of hydrological reactions, two reference years with differing meteorological conditions and glacier mass balances were chosen.

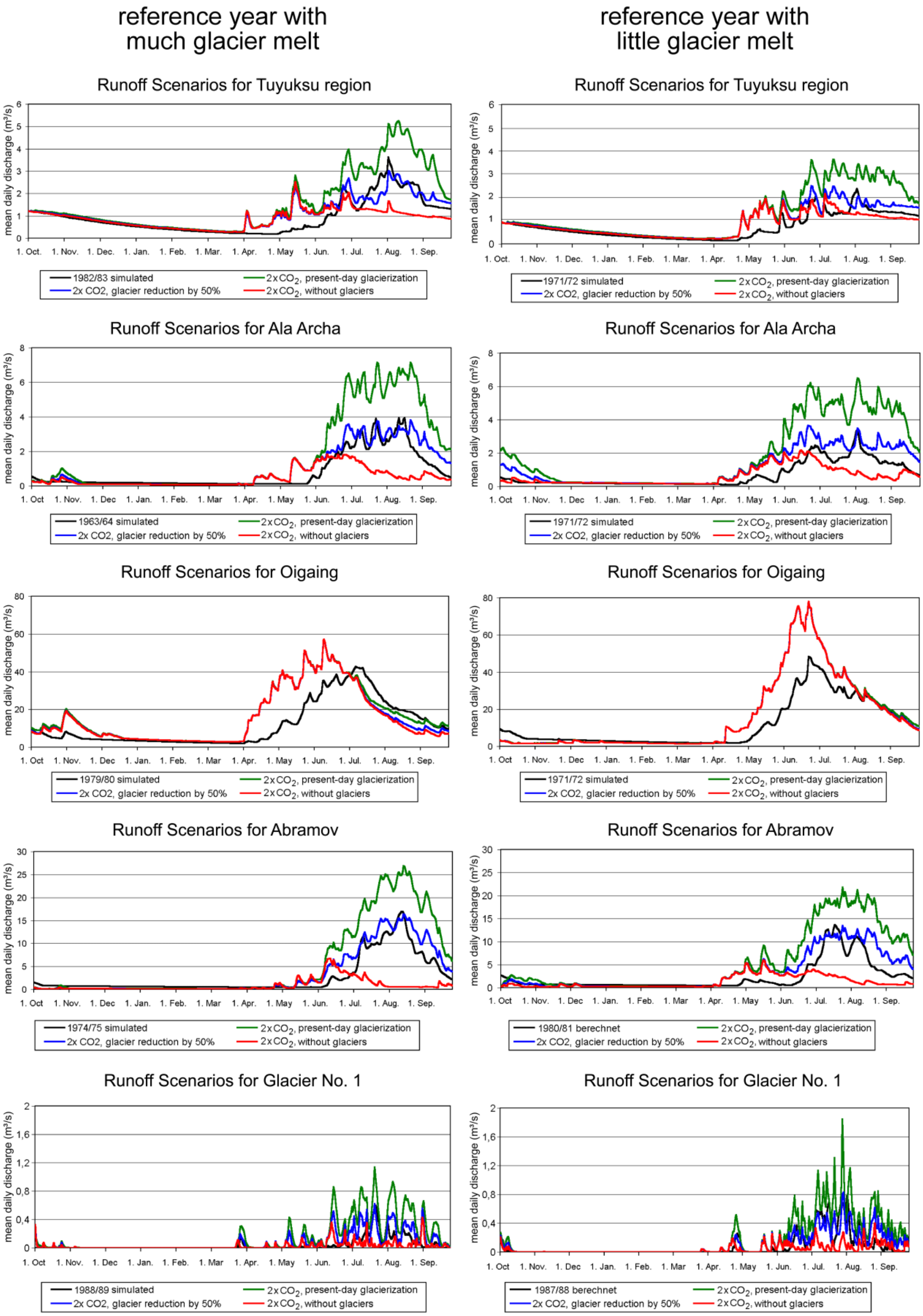

Fig. 12: Calculated daily discharge of the reference years and of a climate scenario after the doubling of CO_2, for three steps of deglacierization. Taken from Hagg et al. (2006).

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/Conclusion

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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