Melting and Evaporation of Glacier Systems in the Hindu Kush-Himalayan Region and Their Possible Changes as a Result of Global Warming

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In Russia, the *Atlas of the World Snow-and-Ice Resources* in which the snow cover and glaciers of the Central Asian region figure prominently was compiled not so long ago. Twenty years back, when we began our work at the *Atlas*, the region in question was almost totally unexplored. In the course of this period, we have developed special procedures that made it possible to establish the principal features of glacial climate, of exogenic mass-and-energy exchange of glaciers, and of glacier-derived runoff formation. In this paper, we present our findings related to the melting and evaporation of glaciers.

The Hindu Kush-Himalayan region is a crucial component of the Central Asian mountain massif which is a chain of the highest mountains surrounding the plateau of Tibet (Fig. 1). The extent of glacierisation in the region is 39, 150sq.km, i.e., glaciers cover 11 per cent of the entire mountain area.

The Hindu Kush-Himalayan region is a giant screen in the way of moisture-carrying air flows coming in from the Atlantic and the Indian oceans. It plays an important role in forming the Tibetan anticyclone and the Indian summer monsoon.

The ridges of the Hindu Kush and the Himalayas, running parallel to one another over hundreds of kilometres, rise from the outer to the inner edge of the mountain land. Therefore, precipitation falling from the incoming air flows declines progressively at the foot of every subsequent ridge but increases up the slope of all the ridges. The creeping nature of the precipitation-forming cloudiness is essential for this process. It is inherent in the frontal cloudiness of the winter Mediterranean cyclones and cold air-mass intrusions which produce maximum precipitation in the Hindu Kush and Hindu Raj in winter and spring.

Figure 2 shows a family of relationships between annual precipitation and the altitude in different orographic regions of Central Asia. These regions are marked in Figure 2. The illustration also presents the distribution of the altitude of the glacier equilibrium line and annual precipitation at the same altitude, in this case at the level of four km. One can see clearly that the amount of precipitation declines, while the altitude of the equilibrium line increases from marginal to interior areas. This means there is a direct relationship between the altitudinal position of glaciers and orographic accessibility of the moisture-carrying air flows. The altitude of the equilibrium line of glaciers in the Hindu

Kush and the Himalayas increases steadily from marginal to interior areas on the leeward macroslopes from 3,500-4,500m to 5,500-5,800m.

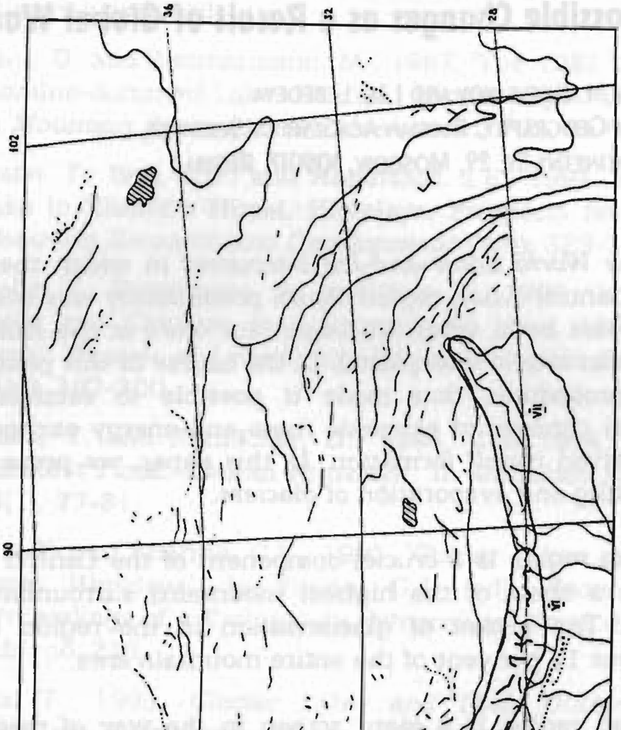

Figure 1: Orographic Sketch of Central-Asia Mountain Massif. Height of Ranges 1) 500-2,000m, 2) 2,000-4,000m, 3) 4,000-7,000m, 4) 7,000-8,000m, 5) rivers, 6) outlines of the Mountain Countries

I) Hindu Kush, II) Hindu Raj, III) Nanga-Parbat, IV) Western Himalayas, V) Central Himalayas, VI) High Himalayas, and VII) Eastern Himalayas

We studied the ablation, melting, and evaporation of glaciers as applied to the altitude of the equilibrium line. At this level, the annual value of ablation, given steady-state glacierisation, is equal to the annual accumulation as well as to the depth of runoff over the year. Climatic conditions that determine the regime and annual value of glacier melting and evaporation exhibit a great diversity in the region in question. The reason lies in great differences in terms of altitude and latitude: from 28°N in the Himalayas to 38°N in the Hindu Kush. Moreover, the differences in circulation processes in the northwestern and southeastern parts of the region produce opposite annual regimes of cloudiness, precipitation, and air humidity.

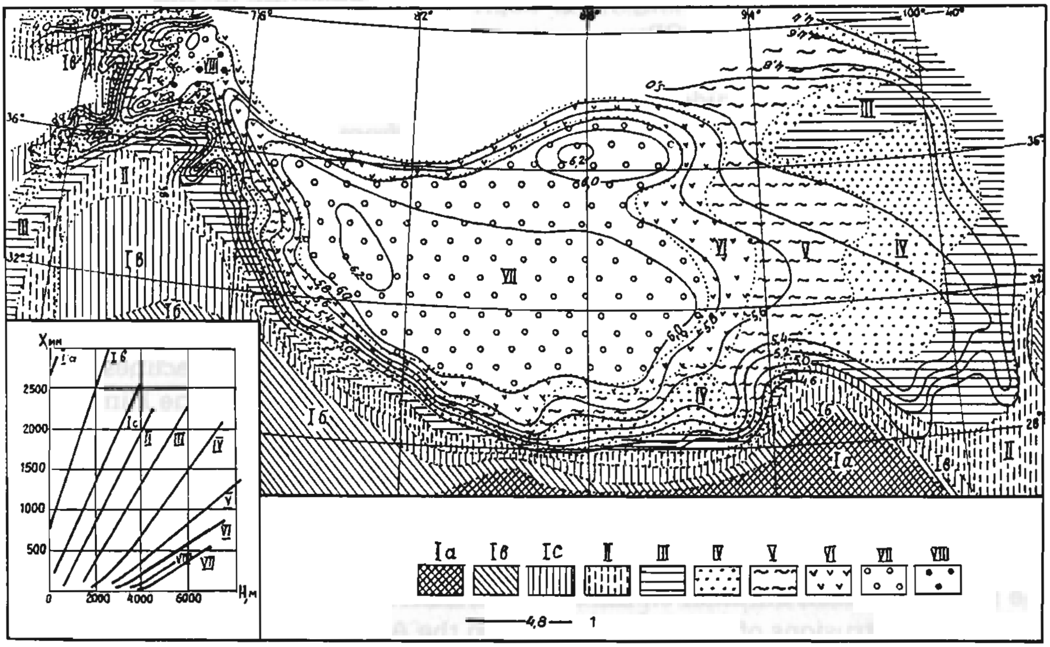

Figure 2: Distribution of the Equilibrium Line on Glaciers

(1) and the annual amount of precipitation at 4,000m in climatological regions:

(2) Ia ->4,500mm, Ib – 4,500mm, Ic – 2,500mm, II – 1,900mm, III – 1,270mm, IV – 600mm, V – 400mm, VI – 220mm, VII -<50mm, VIII – 150mm

On the inset – annual amount of precipitation, X mm, versus altitude, Hm, in climatological regions

The summer temperature of the air-glacier interface on the leeward slopes drops from -4 to -2°C as the elevation increases. The rise of temperature southwards is almost entirely neutralised by the growing monsoon cloudiness. For example, at an altitude of 5,000m in the Greater Himalayas, where cloudiness reaches seven to eight points, the summer temperature is barely around 3°C. During the same period in the Hindu Kush, at a point 10° farther to the north latitude-wise, the temperature is only 3-4° lower. Here, the weather is dry and cloudless, and this is associated with the extensive Asian thermal low.

Because of the cloudiness, the pressure of water vapour increases in the direction from north-west to south-east from three to four GPa to seven GPa and more.

Winter temperature distribution is governed by the latitudinal intensification of solar radiation influx to the south due to the increase of sun elevation and of day duration. At an altitude of 5,000m in the Hindu Kush, the winter temperature of the air above glaciers is equal to -16°C, whereas in the Greater Himalayas it is only -6°C. This difference is further compounded by the annual maximum of cloudiness in the north-west of the region, whereas in the Himalayas cloudiness amounts to three to four points only.

Winter air throughout the region is dry: vapour pressure in the air-glacier interface is equal to 2.0-2.5 GPa.

Thus, the annual amplitude of the air-glacier interface temperature from the Hindu Kush to the High Himalayas drops twofold: from 20 to 10°C, while vapour pressure in the same direction increases from 1-2 to 3-4 GPa.

The processes of circulation that determine the annual regime and distribution of cloudiness and air humidity result in a proper change of the main factor responsible for glacier ablation, viz., total solar radiation. The value of radiation on the glaciers of the southern slope of the Hindu Kush accounts for 90 per cent of the maximum possible when the sky is cloudless and then declines in the southeastern direction, reaching 60-65 per cent on the glaciers of the Himalayas. At the same time, the absolute values of solar radiation influx in these areas are equal to 8.8 and 7.2 MJ/year, respectively. The daily snowfalls and abrupt rises of the surface albedo serve to further weaken the radiation factor of ablation. The frequent summer snowfalls in the Himalayas are due to the monsoon. In the Hindu Kush, such snowfalls are much more seldom: for less than 25 per cent of the summer season duration on the northern macroslope of the Hindu Kush they result from intrusions of cold air masses from the Atlantic and Arctic regions.

We know from field studies of the Pamir and Tien Shan glaciers that the beginning and termination of the melting period coincide with a stable transition of the daily average temperature of the air-glacier interface across -10°C. Once we adhere to this criterion, we can see that, at an altitude of 5,000m in the Hindu Kush, the length of the melting period in the course of a year is around six months, while in the Himalayas this period lasts all year long. The actual manifestation of the process of melting may range from a hardly perceptible moistening of the firn surface, at least for a short time around midday, to intensive melting throughout the day, resulting in the formation of a network of small streams of the surface melt water.

Three main types of melting are distinguished in the Hindu Kush: advective, i.e., very slow melting when the sky is overcast or the weather is dull; radiation and advection, when the most intensive melting at the rate of up to 100mm/day occurs, there being few clouds in the sky; and the radiation type, when melting is appreciable on a cold sunny day. By contrast, in the High and Eastern Himalayas, an advection-and-radiation type of melting occurs during the monsoon period, when slow melting at the rate of 20mm/day continues daily in conditions of continuous and variable cloudiness and snowfalls. When the monsoon is over, a radiation type of very slow melting is established there.

The entire region under study is characterised by snow and ice penitents formed during radiation type melting under an extreme manifestation of weather peculiarities: a massive influx of direct solar radiation, sub-zero air temperatures, and the low pressure of water vapour. In the course of melting, a strong effective radiation and a heavy consumption of heat for evaporation block solar radiation consumption for the melting of the horizontal surface. Only local micro-segments exposed normally to the rays of the midday sun receive some surplus radiation heat, thanks to which depressions on an even surface melt through increasingly, ultimately producing snow and ice penitents (Kotlyakov and Lebedeva 1975).

We determined the annual value of ablation at the equilibrium line of glaciers on the basis of the annual fluctuation of the radiation and heat balance components. Monthly total values of these balances are computed for more than 200 points at the altitude of the equilibrium line.

The radiation and heat balance equation is in the following form:

$$S\,(I+A) + E_{ef} + P + LE = lT$$

where,

S = total solar radiation computed after Berlyand (1961) on the basis of the annual and spatial distribution of cloudiness after Berlyand and Strokina (1980) and vertical gradients of radiation after Barry (1984); see also Fedchenko Glacier (1962);

A = surface albedo, computed using the procedure set out in Oledenenie (1993);

E_{ef} = effective radiation, computed after Yefimova (1961);

LE = consumption of heat for evaporation or release of vapour condensation on the glacier surface;

E = thickness of the layer;

L = heat of evaporation;

lT = heat consumed for melting; here;

T = thickness of the melted layer; and

l = heat of melting.

Monthly evaporation totals were computed by empirical formulas found as a result of measuring evaporation and meteorological elements, viz., vapour pressure, wind velocity, etc on the high glaciers of Pamir-Alay:

$E = 0.0156\,(e_s - e_a)^{1.67}$ at wind velocity < 5m/s,

$E = 13.2\,e^{-2.35}$ at wind velocity > 5m/s.

e_s = maximum pressure near the surface and

e_a = vapour pressure at the air-glacier interface.

P = turbulent heat exchange was computed by the formula:

$P = \rho\, C_p\, K_t\, (t_a - t_s)$,

where,

ρ = air density,

C_p = air specific heat,

$t_a - t_s$ = difference between air temperature and surface temperature,
K_t = turbulence coefficient.

Because the coefficient K_t is the same for heat exchange and moisture exchange, we derived it from the following formula:

$$K_t = LE/\rho\, a\, \Delta e,$$

where,
$\Delta e = e_s - e_a$;
a - a factor for converting absolute air humidity into specific air humidity.

The temperature of a glacier surface as well as its annual fluctuation and daily regime in different weather conditions has been studied earlier (Oledenenie 1993), and these data were used in all computations as required. The pressure of vapour at the air-glacier interface, knowledge of which is also essential, was determined from a nomogram drawn on the strength of data from observations throughout the Asian glaciers, including those of the Himalayas (Ageta et al. 1980) and combining vapour pressure, cloudiness, and the temperature of the air-glacier interface.

Presented in Figure 3 is the distribution of the annual value of ablation at the altitude of the glacier equilibrium line and the evaporation component in that value. One can see clearly that the rate of ablation decreases from the marginal to the interior parts of the mountains. This is due to both the smaller amount of atmospheric precipitation and its lower concentration on the glaciers. Concentration values are shown in the illustration by digits in small circles. A maximum ablation of 400mm/year is noted on the north-western slope of the Hindu Kush and is attributed to good humidification from Mediterranean cyclones; it is here, in the deep incisions on the outer surface of the Nanga Parbat massif, that relief features are rather favourable for the concentration of precipitation.

Ablation of glaciers along the outer rim of the High and Eastern Himalayas is equally strong, and this is due not only to their extremely steeply sloping relief, but also to the close vicinity of the Bay of Bengal, from whence the main monsoon flow rushes on to the continent. The least humidified are the Western and Central Himalayas, completely shut off from the winter cyclones, while the monsoon reaches them in an already weakened intensity. Here, the maximum ablation on the windward macro-slope equals 2,000mm/year. By and large, on the leeward macro-slope of the Hindu Kush and the Himalayas ablation amounts to around 500mm/year, which is four to eight times less than on the windward side.

Evaporation from the glaciers of the Hindu Kush-Himalayan region is maximal (viz., the first hundreds of millimetres per annum) along the periphery of the Hindu Kush glacier system, which can be put down to the dry and clear weather

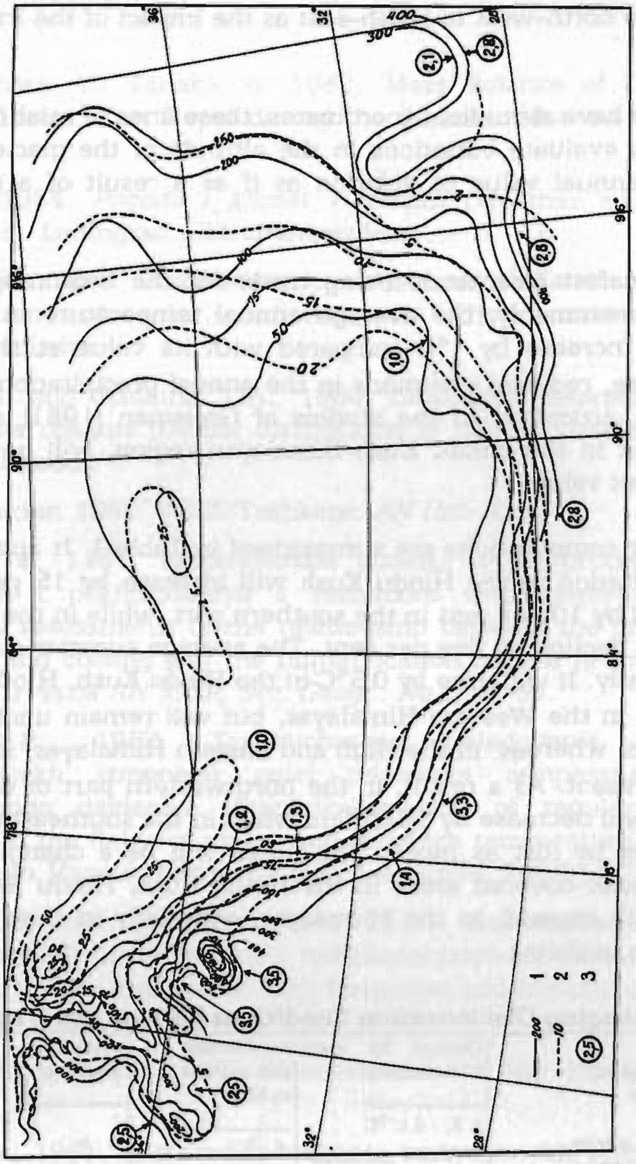

Figure 3: Annual Ablation A Pattern g/cm^2 (1) at Glaciers ELA and Evaporation Part in Percentage (2) Values in Circles (3) Concentration coefficient $K = \frac{A}{X}$, X – Annual Solid Precipitation at ELA

during the period of melting. However, in view of the extremely high values of melting, the ratio of evaporation to glacier ice mass wasted does not exceed five per cent. In interior regions, in absolute terms, the value of melting is lower, but the melting component in ablation goes up to 20 per cent. This correlation of the melting and evaporation percentages is observed throughout the Hindu Kush-Himalayan region. The only exception is in its eastern part where summer evaporation gives way to condensation due to the saturating humidity of the monsoon air masses very active there. For the rest of the year this part, too, is dominated by evaporation.

The annual value of ablation and the mean summer temperature are interrelated. In the studied area, we discovered five lines of relationship that reflect the decreasing ablation of glaciers at the same summer temperature in the direction from north-west to south-east as the impact of the Indian monsoon increases.

Because they also have altitudinal coordinates, these lines of relationship make it possible to try to evaluate variations in the altitude of the glacier equilibrium line and in the annual value of ablation as if as a result of a global climate change.

At present, the safest forecast is being made for the beginning of the 21st century, when, presumably, the average annual temperature in the northern hemisphere will increase by 1°C compared with its value at the end of the 1980s. In this case, regional variations in the annual precipitation and seasonal air temperatures, according to the studies of Groisman (1981) and Kovyneva (1982) carried out in the Hindu Kush-Himalayan region, will have a different sign and a different value.

The results of our computations are summarised in Table 1. It appears from the table that precipitation in the Hindu Kush will increase by 15 per cent in the northern part and by 10 per cent in the southern part, while in the Himalayas its amount will even decline by five per cent. The average summer air temperature will change similarly. It will drop by 0.5°C in the Hindu Kush, Hindu Raj, Nanga-Parbat, and even in the Western Himalayas, but will remain unchanged in the Central Himalayas, whereas, in the High and Eastern Himalayas, it will be 0.5°C higher than at present. As a result, in the northwestern part of the region, the equilibrium line will decrease by 50-200m, while in the southeastern part it will rise approximately by just as much. The result will be a changing pattern of glacierisation: glacier-covered areas in the Hindu Kush, Hindu Raj, and Nanga Parbat massifs will expand; in the Himalayas, especially in their eastern part, glaciers will begin to shrink.

Table 1. Changing Glacierisation Conditions Early in the 21st Century

Mountain country	Glacier Glaciological levels, m glacier : glacier heads : termini:	Change by early 21st century Δ X, : Δ t, °C mm/year % :sum- :win- mer : ter	Equilibrium line altitude, m ELA a : b :	Ablation A, mm/year : a : b :	Δ ELA, m	Δ A, mm/year
Hindu Kush	5,000- : 3,200- 6,500 : 4,000	10-15: -0.5 : -0.5	3,500- : 3,280- 5,200 : 5,050	8,000- 9,200- 1,600 : 1,750	-220 -150	1200 150
Hindu Raj	6,400 : 3,600- : 4,000	10 : -0.5 :0.0	3,800- : 3,580- 4,800 : 4,600	6,450- : 7,100- 2,600 : 2,900	-220 -200	650 300
Nanga Parbat	6,500 : 2,900-: 3,670	5 : -0.5 : 0.0	4,200- : 4,000- 5,200 : 5,100	7,400- : 7,800- 3,200 : 3,340	-200 -100	400 140
Western Himalayas	: 3,300- 6,500 : 5,000	: : -5 : -0.5 : 0.5	4,500- : 4,450- 5,000 : 4,950	5,100- : 4,850- 3,400 : 3,230	-50 -50	-250 -170
Central Himalayas	: 3,700- 6,500 : 5,000	: : -5 : 0.0 : 1.0	5,000- : 5,070- 5,500 : 5,550	3,100- : 2,950- 1,700 : 1,600	70 50	-150 -100
High Himalayas	6700 : 4,500- : 5,500	-5 : 0.5 : 1.0	4,500- : 4,720- 5,800 : 5,920	4,400- : 4,180- 750 : 650	250 120	-220 -100
Eastern Himalayas	: 2,900- 6,500 : 4,000	: : -5 : 0.5 :0.75	4,500- : 4,720- 5,200 : 5,350	4,400- : 4,180- 2,200 : 1,900	220 150	-220 -300

a - current value

b - anticipated value early in the 21st century

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