Distribution of Snow Cover in the Mountains of Central Asia

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Abstract

The problems of snow cover estimation in mountainous areas are still unsatisfactorily solved. The main cause is the acute shortage of up-to-date information on the distribution of precipitation and snow cover in mountains: from the standard observations it is impossible to determine the snow conditions in most of the mountain areas by earlier methods. The methods of remote sensing that are successfully used for snow cover estimation on plains still do not give satisfactory results for mountainous regions. The author has developed a method that allows the snow conditions of any mountain territory, including regions that have not been studied, to be evaluated. Based on this method, the main regularities of snow cover distribution in the mountains of Central Asia have been obtained, and the influence of zonal, regional, and local factors on the distribution and regime of seasonal snow cover in mountains has been investigated.

Basic Data

Methodical evaluations have been mainly based on the means of standard long-term snow observations in the Pamir, Tien Shan, Gissaro Alai, Altai, Caucasus, Dzhungarsky Alatau, and in the Alps. Standard data on precipitation in mountains and information contained in the glacier-inventory and other scientific publications in the fields of hydro-climatology and glaciology for the Hindu Kush-Karakoram, Tibetan plateau, and Kunlun were mainly used.

The method of assessing the influence of local factors on the distribution of snow cover is based on data from many year-round measurements in a special snow measuring network (northern Tien Shan), including 35-60 (depending on the year) snow survey sites which differed in absolute height, exposure, and underlying surface.

Method

The method of calculation is based on identification of general spatial dependencies of snow parameters (such as the dates of formation and destruction of snow cover, depth, and water equivalent of snow) on absolute elevation, taking into account zonal, regional, and local factors. Very important components of the calculation model are the height of the 'inferred' firn line (climatic snow line on the glaciers) and the annual sum of solid precipitation and the maximum snow storage at this level.

The method of calculating the elevation of the inferred snow line, H_c, is based on the empirical dependence of the mean elevation of the firn line, H_f, on the glacier area F. In the mountain regions of the world (Eurasia, North America) this dependence has an asymptotic character and similar parameters that have made it possible to generalise the implications of definitions into a unified universal relationship (Fig. 1). It has been found that the glacial range in mountains decreases sharply as the glacier area increases to a certain limit, and it does not depend on the morphological type of glacier and on increasing area (Severskiy and Blagoveshchenskiy 1983).

For regions with a deeply dissected relief of glacial zone the limit is $F=14km^2$; in regions with a weak relief (< 500m), where smooth flat surfaces are widely developed in the glacial zone, the limit is $F=8km^2$.

The corresponding equations for calculating the lower limit of a field of empirical points (Fig. 1) are:

in the first case

$$H_c = H_f + 670^* 10^{-0.155\,F}$$

and in the second case

$$H_c = H_f + 450^* 10^{-0.28\,F}$$

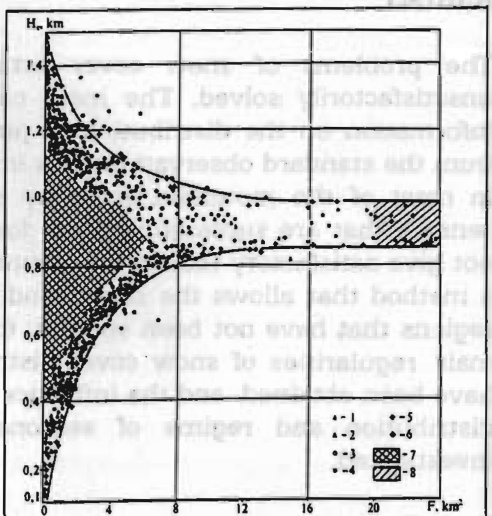

Figure 1: Dependence of the Height of the Firn Line, H_f, upon the Glacier Area, F. 1 - Altai, Sayany; 2 - Dzhungarsky Alatau; 3 - Tien Shan; 4 - Pamir-Alai; 5 - Big Caucasus; 6 - Alps; 7 - entire field of points; 8 - zone where the glacier area is shown out of scale (F≥20sq.km)

The mean square deviation of the values of H_c calculated from equation (1) and the observed values does not exceed 21 ± 3m. These equations have been used for the calculation of H_c for the basins, given the information about the glacier area and firn line elevation. The calculation of H_c for regions where such information is not sufficiently available is made on the basis of the empirical relationship between the climatic snow line elevation and upper border of forestry (H_{for}) or bush (H_b), (Fig. 2). These relationships are the same for the mountain regions of Eurasia:

$$H_c = 1.11\, H_{for} + 0.69 \quad (3)$$

$$H_c = 1.12\, H_b + 0.30 \quad (4)$$

where,

H_{for} and H_b are the corresponding heights in kilometres. Maps of the inferred snow line, H_c, annual accumulation of solid precipitation, A, and maximum snow storage, W, at the elevation of H_c in the mountains of Central Asia have been drawn in accordance with the obtained results. The values of A are calculated by the empirical formula of Krenke-Hodakov depending on the average summer air temperature at the elevation, H_c, the values of W_c being determined from the equation:

$$W_c = A - X_a/K^2 \quad (5)$$

where,
K is the coefficient of snow concentration at the surface of glaciers due to redistribution by wind and avalanche action; X_a is the total precipitation at the height, H_c, during the ablation period.

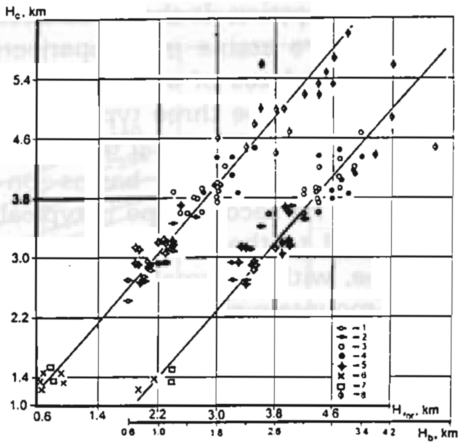

Figure 2: Relationship of the Height of the Inferred Firn Line, H_c to the Height of the Upper Timberline, H_{for}, and Sub-alpine Bush, H_b. 1- Altai and Sayany; 2 - Dzhungarsky Alatau; 3 - Tien Shan; 4 - Pamir and Gissaro-Alai; 5 - Caucasus; 6 - Urals; 7 - Kamchatka; 8 - Himalayas, Karakoram, Tibet, Alashan.

Calculation of the distribution of snow characteristics versus altitude is based on typification presented by the author: for the conditions in the Pamirs, Tien Shan, Dzhungarsky Alatau, and Altai, eight types of vertical distribution of maximum snow storage and three types of distribution of the duration of snow period versus altitude were found (Severskiy and Blagoveshchenskiy 1983, Severskiy and Pimankina 1980). Using these typical dependencies and data on W_c, it is possible to calculate the altitudinal distribution of the snow characteristics within the range of ±20% for any basin where information has been collected at least for one pointed level. For regions with gaps in information, the calculation of snow parameters can be made on the basis of data on maximum snow storage at the climatic snow line (Severskiy and Blagoveshchenskiy 1983).

Results

An analysis of all available information on snow cover in Eurasia - from the Alps in the west to the Altai-Sayany Mountains in the east, and from the Khibins and Fennoscandia Mountains in the north to the Pamirs and Karakoram in the south - made it possible to reach the conclusion that the distribution of snow cover in the mountains of inner-continental regions is caused by the following general regularities.

(a) Similar conditions of relief and location of an area relative to the mountain periphery call forth specific types of distribution of snow parameters, which are closely related to the absolute height and geographical coordinates of the site in question. It should be noted that the distribution of the period of snow cover is more stable in comparison with the distribution of maximum snow storage. The dates of stable snow cover in the mountains of Central Asia are grouped under the three types of vertical distribution (Table 1). The first type, with the strongest vertical gradients under the considered conditions, is typical of orographically open basins on the western periphery of mountainous countries. The second type is typical of peripheral basins unfavourably oriented with regard to the prevailing directions of moisture-bearing air streams. The third type, with the smallest vertical gradients, is valid for orographically closed interior mountain regions.

All three indicated types are the same in terms of the character of the vertical distribution during the period of formation of the stable snow cover. The largest differences are found in the periods of snow cover decay. This can be explained by the fact that the formation of snow cover is influenced by both the precipitation regime and temperature conditions, which vary more or less smoothly over the territory, whereas the differences in periods of snow cover decay mainly depend on the values of total snow storage.

Table 1: Typical Equations for Calculating the Mean Dates of Formation and Destruction of Stable Snow Cover in Mountains

Type of distribution	Region	Equation	Altitudinal range (masl)
1	Open basins on the western periphery of mountains	$\Delta T_m = 17 - 1.5H - 0.025H^2$ $\Delta T_d = 0.88H + 0.086H^2 - 16$	600 - 2,800 600 - 3,400
2	Peripheral mountain basins (excluding western)	$\Delta T_m = 14 - 0.9H - 0.035H^2$ $\Delta T_d = 0.11H^2 - 1.1H$	600 - 2,800 600 - 3,400
3	Intra montane regions, mountain valleys	$\Delta T_m = 3.0 - 0.325H^2$ $\Delta T_d = 0.039H^2 - 0.03H - 4$	600 - 3,400 600 - 3,400

$\Delta T_{m,d}$ - difference between the dates of formation (m) and destruction (d) of stable snow cover at a height of 1,000m and at a calculated level H, in days.

The vertical distribution of maximum snow storage varies more considerably: for the same territory, eight types of snow storage distribution at an absolute elevation have been found (Severskiy and Blagoveshchenskiy 1983), three of which are shown in Table 2.

Table 2: Typical Dependencies of Maximum Snow Storage on Absolute Height

Type of distribution	Equation	Variance (σ) mm	Variance (σ) %	Altitudinal range (masl)
Central-Tian Shan	$\Delta W = 5.2\ H^{2.00}$	25	-	600 - 3,400
North-Tian Shan	$\Delta W = 13.6\ H^{2.30}$	23	14	600 - 3,200
West-Tian Shan	$\Delta W = 94.5\ H^{2.20}$	50	15	600 - 2,600

ΔW - difference between maximum snow storage at "zero" (600m) and at a calculated level, in mm. H - absolute height km.

(1) This type of distribution, other factors being equal, is determined by the orientation of the macroslopes of mountain regions towards prevailing directions of the moisture-bearing air streams (Fig. 3). The moisture transport in continental mountains is not constant. In the Caucasus, in cold periods, the main axis of the moisture transport is directed from the south-west to the north-east at an angle of 60° to the meridian, while in the Pamir, Gissaro-Alai, and Tien Shan this angle is 40°. Further to the north, the prevailing direction of moisture flow is closer to the west. In the Dzhungarsky Alatau, the maximum snow storage corresponds to azimuths of valleys, $A_z \approx 250°$, and in the Altai, $A_z \approx 270°$.

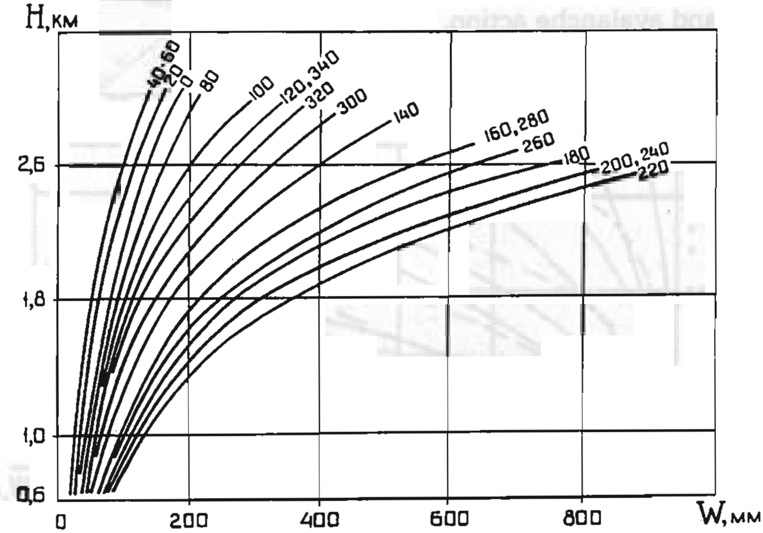

Figure 3: Typical Relationships of the Norms of Maximum Snow Storage, W, to Absolute Altitude, H, and Orientation in the Peripherical Regions of the Tian Shan, Pamirs, and Gissaro-Alai (Figures next to the curves are the azimuths of the main valleys.)

(2) The vertical gradient of snow storage in the major snow basins decreases from the west to east (Fig. 4): the largest values of the gradient dW/dH characterise the western slopes of the Scandinavian mountains. These values are reduced by half in the West Caucasus and even more at the western periphery of the Tien Shan and Altai. Within separate regions, changes of snow storage in the direction from west to east are not substantial in comparison with the change as a function of absolute elevation in geographic latitude.

(3) The influence of the effects of mountain massifs and orographic barriers is clearly indicated in the distribution of snow cover on mountains. The first effect is apparent in the linear decrease of snow storage from the periphery to interior of the mountainous country. The second effect is indicated by the sharp contrasts of snow conditions on the windward and leeward slopes of mountain ranges, which represent obstacles to the moisture-bearing air streams. A clear example of this effect is the distribution of the snow storage on the slopes of the Koksu Range in the Altai (Fig. 5). In the Uba River basin, as one approaches the Koksu Range, snow storage drastically increases to a maximum at the ridge zone, with a drastic decrease beyond the ridge; at a distance of 40-50km the values decrease to those typical of the vast interior mountain region of the Altai.

(4) In the mountains of the inner-continental regions of Eurasia, the maximum snow storage continuously increases with altitude to the climatic snow line elevation. From available information, one can confirm that the snow storage above the snow line increases with elevation, at least to elevation contours to 200-400m below the ridges surrounding the mountain glacier basin (excluding separate peaks); above this level and approaching the watershed

ridges, the snow storage decreases in accordance with the redistribution of snow due to wind and avalanche action.

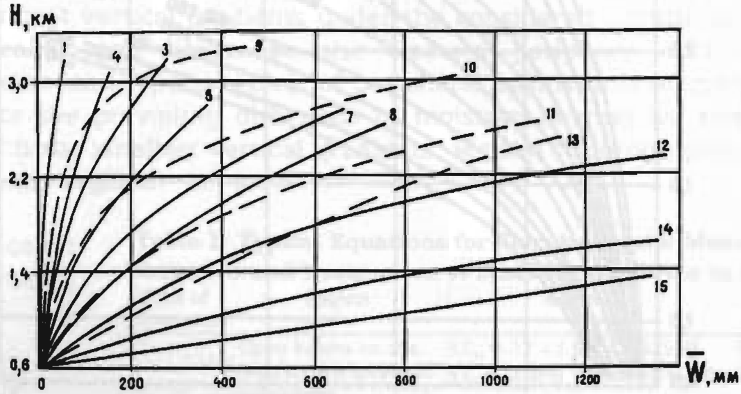

Figure 4: Correlation of the Typical Distribution of the Normalised Maximum Snow Storage, W, versus Absolute Altitude, H, for the Various Mountain Regions of Eurasia (1-8 - mountain regions of Central Asia and Kazakhstan (see Tab. 1); 9 – intramontane regions of northern Caucasus; 10 - peripherical regions of Northern Caucasus; 11 - central Caucasus (southern slope of Big Caucasus); 12 - Western Caucasus; 13 - interior regions of southern Norway; 14 - interior regions of northern Norway; 15 - western coastal parts of southern Norway.)

(5) In most mountain regions, substantial redistribution by wind is found only above the forest line; it is especially large in ridge regions of the glacier névé zone. Relatively large snow storage at the forest line is a result of the redistribution of snow by wind. The second maximum of snow storage is in many basins found in the lower third part of slopes in closed river valleys and at distances of 200-400m below the ridges.

Characteristics due to local factors are superimposed on the general spatial pattern of snow conditions in the mountains. Among the local factors, the orientation of slope, character of vegetation, and wind conditions influence the distribution of snow cover. In some cases, the horizontal contrasts are larger than the vertical ones. Thus, regarding influences on the period of snow cover in the Zailiiskiy Alatau, a change of orientation from north to southwest corresponds to a change in absolute elevation by more than 1,000m (Severskiy and Severskiy 1990, Severskiy and Severskiy 1992, Sosedov 1967). With the vertical gradients of maximum snow storage characteristics of the Zailiiskiy Alatau, a change of orientation from north to east (west) corresponds to a decrease of absolute elevation by almost 1,000m. However, the decrease of snow storage from meadow slopes to coniferous forest is twice as high as the change corresponding to a decrease in absolute elevation from 2,500 to 1,500m.

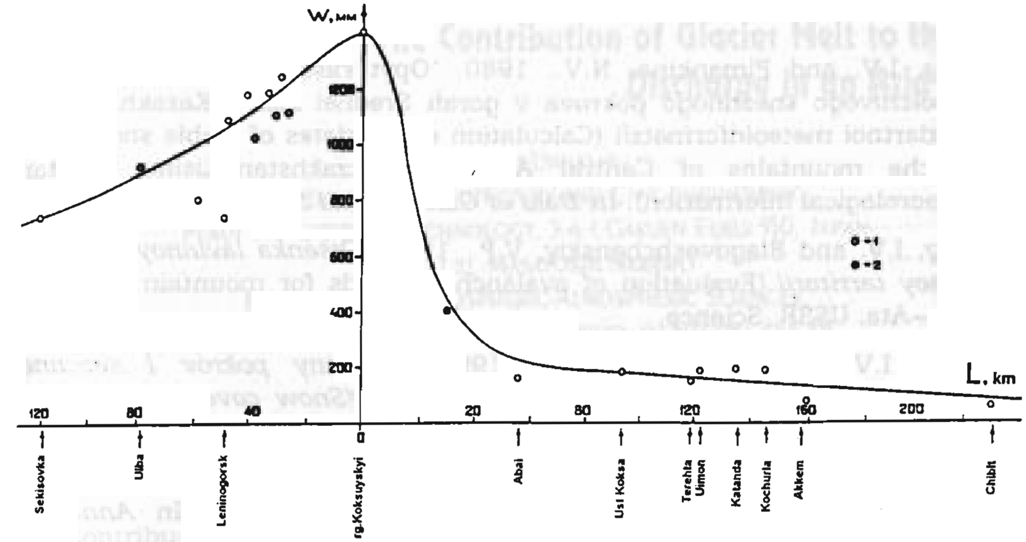

Figure 5: Distribution of Maximum Snow Storage (reduced to the height of 2,000m) in the Altai in Relation to the Distance from the Orographical Barrier (Koksu Range) (1 - Sites of the snow survey measurements; 2 - precipitation gauges.)

In other words, the influence of slope orientation and character of vegetation in the temperate snow region is larger than the influence of the absolute elevation. As one progresses towards snowier regions, contrasts in exposure diminish. In the snowiest regions at the western periphery of mountainous country, these differences are small, and determined by differences of exposure and by loss to total snow evaporation.

The characteristics of the distribution of snow cover in the mountains as considered here are found in all interior continental regions of Eurasia. A comparative appraisal leads to the conclusion that the horizontal distribution of snow conditions due to the macro-orientation of slopes, along with location of the regions with respect to the periphery of the mountainous areas, and the influence of local factors, weighs more heavily than interregional and vertical differences. On the basis of the results obtained for the territory of the Tien Shan, Pamirs, Gissaro-Alai, Dzhungarsky Alatau and Altai, maps of the height of the climatic snow line and the annual amount of solid precipitation at this level have been drawn for these regions, together with maps of the dates of stable snow cover and maximum snow storage as well as of the maximum snow storages for the Hindu Kush-Karakoram, Tibetan plateau, and eastern Tien Shan. All these maps were prepared for the *Atlas of Snow and Ice Resources of the World*.

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