ACCUMULATION, ABLATION, MASS BALANCE, AND RUNOFF FROM GLACIERS

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Summary

Glaciers are formed as a consequence of the accumulation and transformation of solid atmospheric precipitation under long-term positive ice balance. The accumulation area of a glacier is situated in the upper part where the majority of accumulation takes place, while the ablation area is situated in the lower part where the ice expenditure runs. An equilibrium line divides areas of accumulation and ablation on a glacier, and a firn line goes above this which marks the lower boundary of the firn area on a glacier. The most important characteristic of a given glacier's regime is the altitude gradient of its balance near the equilibrium line which indicates energy of glacierization or, in other words, the glacier activity index. The mass of a glacier increases due to deposition of atmospheric precipitation (snow, rain, etc.) falling and building up on its surface and also by snow drifting during snowstorms, and snow and ice avalanching. The glacier mass decreases due to melting, evaporation and snow blowing off, ice falling and icebergs calving. From correlation with a mean temperature of three summer months one can determine a melting rate and amount of mass loss for the whole ablation period. The majority of water from melted snow runs down along surface channels which are formed on the glacier tongue. A system of aquifers exists inside glaciers. The total amount of liquid water in a glacier is usually equal to 1-2% of its total mass. Runoff of waters from melted seasonal snow, firn and ice, together with liquid precipitation, converges into a river on the glacier surface that is called the glacier-derived runoff. Glaciers are natural regulators of their own runoff, a process that can be usefulfor human populations. The glacier-derived runoff increases during low-water years when

precipitation is scanty. The runoff from glaciers is concentrated in summer, a dry period in the majority of glacier regions. Also, runoff is redistributed from the first to the second half of a summer. All these variations of the runoff caused by glaciers are very convenient for irrigation while the long-term regulation is important for hydraulic power engineering.

There are two main types of glacier floods; the first are ones caused by melting of ice, firn and snow on a glacier, and the second type is the result of water discharges from inter-glacier cavities or glacier-dammed lakes. The latter type of floods are the most dangerous. A significant amount of water from melted snow is repeatedly frozen within a thickness of firn and ice, and it is the internal accumulation of glaciers. The relationship between the addition and expenditure of snow and ice mass on a glacier over a specific time is known as the glacier's mass balance.

1. Introduction

Glaciers are formed as a result of the accumulation and transformation of solid atmospheric precipitation if their long-term balance is positive (i.e., gains in snow out-mass losses in runoff, icebergs calving, etc.). The ***accumulation area*** is situated at the upper part of a glacier where the precipitation is mainly accumulated, while the ***ablation area*** is placed in the lower part where the precipitation is expended (Figure 1). Usually, the upper part of a mountain glacier is actually a firn basin. It occupies a bowl that is the widened head of a valley and has a concave surface. The upper edge of the firn basin enters depressions between offspurs of a ridge surrounding the bowl. When flowing out from the bowl, a glacier often crosses a high mouth step, i.e., riegel; here, the ice is dissected by deep cross crevasses, and an icefall arises. And, further on, the glacier descends down the valley in the form of a relatively narrow tongue, sometimes creating tributaries from its sides.

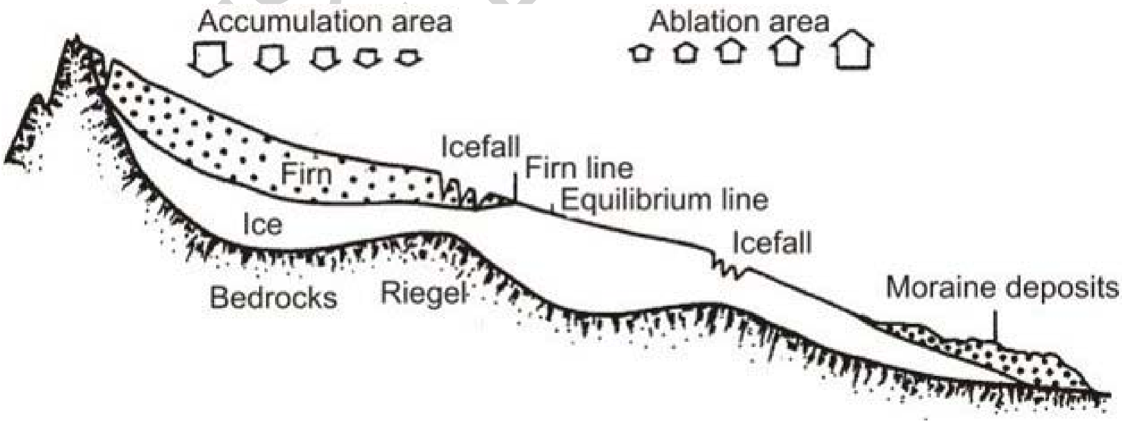

Figure 1. A pattern of a mountain glacier

A glacier's life is determined by a mass balance. When the balance is positive, i.e. the glacier income exceeds its expenditure, the ice mass increases, the glacier becomes more active and advances, occupying new areas. When the balance is negative, the ice mass decreases, and the glacier becomes passive, and retreats, thus, vacating from under the ice the valley and slopes earlier covered with this glacier.

A state of glacial mass balance is reflected in the equilibrium line. Thisis the most important boundary level on a glacier. The equilibrium line is drawnwhere accumulation, as a whole for a year, is equal to the loss, or ablation, for that same time period. The equilibrium line indicates the divide between the areas of accumulation and ablation. Slightly above this line, a firn line passes. It forms the lower boundary of the firn area on the glacier, where snow or firn is present on the glacier surface throughout the year. A rather narrow band of ice is placed between the equilibrium and firn lines; this ice is usually formed during the last summer season by the freezing of snow saturated with melting water.

The mass balance of a glacier is finally summarized at the end of summer when melting is over, and a boundary of snow and firn holds in a given year the highest position. Clearly a close correlation is established between the boundary position and the glacier mass balance: the greater the negative mass balance, the higher the placement of the firn boundary on the glacier. Aclose linear correlation between both indices is obtained for glaciers over a 20-30 year period of observations.

2. Regime of glaciers and the energy of glacierization

A glacier regime is determined by such quantitative indices as the equilibrium line altitude, intensity of the accumulation/ablation processes (annual amount of accumulation at the equilibrium line altitude), total area of both accumulation and ablation zones, glacier coefficient, altitude gradients of accumulation and ablation and a sum of them, i.e. the altitude gradient of the balance. In different years, each of these indices varies at a specific glacier, indicating apermanent state of fluctuation. Figure 2 shows a diagram demonstrating how with elevation on a glacier the accumulation grows, and the ablation decreases. The faster these processes run with the elevation change, the greater is their altitude gradient, the greater is the mass exchange at the glacier, the more active is the glacier life.

The most important characteristic of the glacier regime is the balance altitude gradient near the equilibrium line, or a tangent of inclination angle of the curve that expresses the dependence of the balance upon altitude. This quantity is called the ***energy of glacierization***, or a glacier activity index:

$$e = \gamma_c + \gamma_a,$$

where e is the energy of glacierization, γ_c is a vertical gradient of accumulation (it is positive when accumulation grows with elevation), γ_a is a vertical gradient of ablation (it is positive when ablation decreases with elevation); it is expressed in terms of *mm* of a water layer (or in $g\ cm^{-2}$) per 1 *m* of elevation.

Graphs showing the relation of the specific mass balance of a glacier and its components, i.e. accumulation and ablation, compared to the altitude are called ***balance***

curves. These are widely used for analysis of a glacier's balance and regime in different altitude zones and their variability from year to year. The mass balance in $g\ cm^{-2}$ (or in meters of a water equivalent) is plotted along the ***x***-axis, and the altitude is along the ***y***-axis. It is shown in Figure 3 that the balance curve forms do not change much from year to year for the same glacier. Depending on the absolute value of the mass balance, only a displacement of the curves aside from that corresponding to the glacier's stationary state takes place.

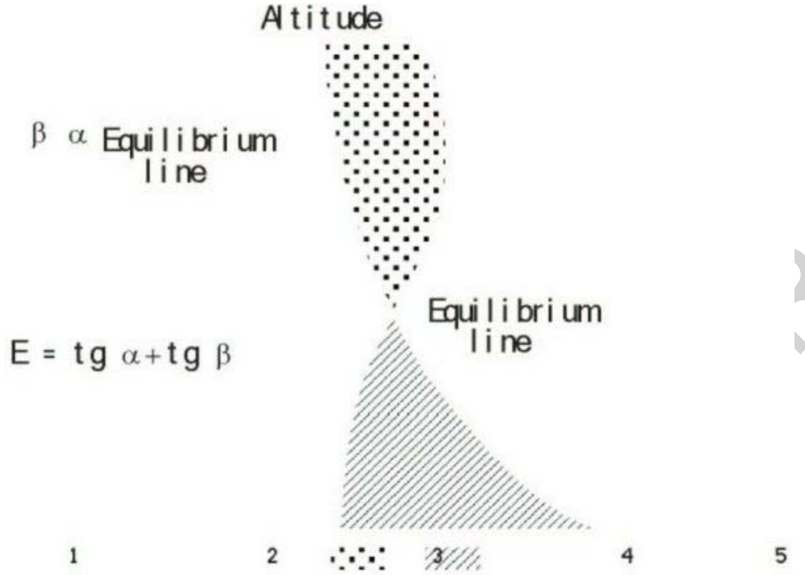

Figure 2. Explanation of the energy of glacierization:
1 - accumulation; 2 - ablation; 3 - mass balance; 4 - area of the ice accumulation; 5 - area of ice ablation

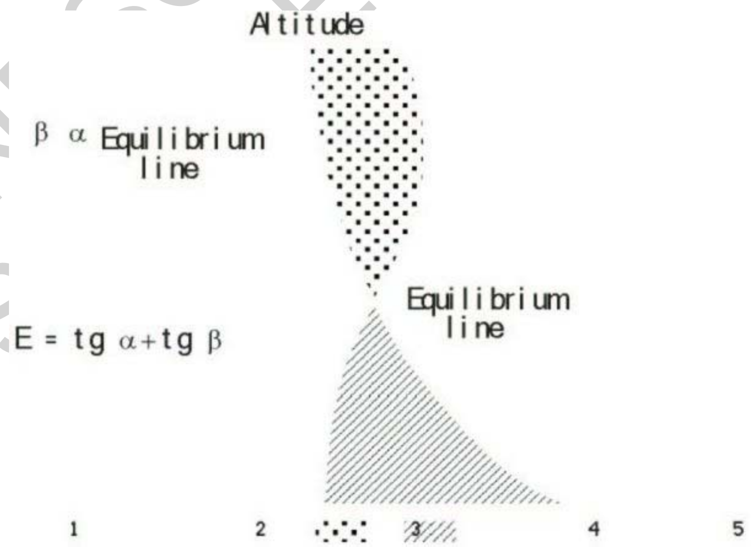

Figure 3. The balance curves for the South Cascade Glacier in the western USA for 1958-1964

Within the accumulation area, the mass balance of a glacier is the annual gain of firn and snow ***C***, and within the ablation area it is the annual ice loss ***A***. On the basis of the idea of "energy of glacierization" = ***e***, we may write for both areas of accumulation and ablation the following equalities:

$C = e(H - H_0)$ and $A = e(H_0 - H)$,

where $\boldsymbol{H_0}$ is the equilibrium line, and ***H*** is a height of any point.

The altitude gradient of the mass balance increases with the growth of the accumulation/ablation processes and, thus, characterizes the glacier's activity: its flow velocity, the intensity of the mass exchange in the glacier, and the relief-forming activity of the ice wrought upon the earth surface beneath it. On the whole, values of the mass balance gradients increase if one moves from poles to the equator, and they increase still more as one looks from continental regions to marine . If at outer coastal Alaskan ranges the ***e*** values reach 20-22 $mm\ m^{-1}$, one would find at the Tibetan high plateau they amount to only 2-3 $mm\ m^{-1}$.

Values of glacierization energy are not uniform within mountain ranges. They are always higher on glaciers lying on slopes leeward to air masses bringing moisture, and they are well lower in inner parts of a massif. The distinctions are especially great in mountain systems located on permanent ways of a moist air mass advection; Alaska may serve as an example. The altitude gradient of mass balance at the Lemon-Creek Glacier which is located in southern near-coastal Alaskais equal to 22 $mm\ m^{-1}$, while at the Mack-Call Glacier at the inland Brooks mountain range it comes to only 2 $mm\ m^{-1}$. Smaller, but similar differences between the ***e*** values are noticed in outer and inner ranges of the Altai, Pamirs, Tibetan, etc.

Similar to mountain glaciers, the mass balance gradient of polar glaciers decreases as one moves farther from sources of moisture and away from prevailing cyclone trajectories. In Iceland the ***e*** value is equal to 9-11 $mm\ m^{-1}$, while at the Severnaya Zemlya it is only 2-4 $mm\ m^{-1}$.

The "energy of glacierization" notion is not applicable for the Antarctic ice sheet since the equilibrium line there mostly runs at sea level, and virtually all ice loss is due to the calving of icebergs. Glacierization activity can be estimated here from the ice flow velocities that are equal here to 500-1500 $m\ year^{-1}$ at places of significant concentration of runoff and much smaller at other parts of a glacier's edge. With regards to the huge radius of the Antarctic ice sheet (1500-2000 *km*) it should be admitted that the ice flow velocities here observed testify to a rather low energy of glacierization, but that does not contradict the conclusion that the Antarctic ice sheet as a whole demonstrates a great amount of activity, owing to its giant size.

Important indicators of a glacier's activity are two coefficients: the so-called glacier coefficient $\boldsymbol{K = S_c/S_a}$ which is the ratio of the accumulation area to the ablation area, and the accumulation area ratio K' $\boldsymbol{= S_c/(S_c + S_a)}$. These coefficients are clearly connected by simple relationships:

$K = K'/(1 - K')$ and $K = K'/(1 + K)$.

The value of the glacier coefficient which corresponds to the glacier's stationary state decreases when the energy of glacierization reduces. The notion of both indicated coefficients is not useful in the cases of those glaciers where the primary ice loss proceeds from iceberg calving. Thus, the ablation area of the Antarctic ice sheet is equal to 150 thousand square kilometers, and it is about 1% of the total area of Antarctica, i.e. the glacier coefficient is 100. The last figure testifies to only a minute significance of the surface ablation for the ice loss of the Antarctic ice sheet, but it does not relect any characteristics of the whole glacier.

3. Accumulation processes

A period of accumulation on a glacier is a part of a balanced year during which the mass income on the glacier exceeds its loss . Increase of a glacier's mass is accounted for by atmospheric precipitation, snow accumulation during snowdrifts and by avalanches. The primary source of accumulation is solid precipitation (snowfall) related mainly to cyclone activity. Because of that, many glaciers are developed along main cyclone trajectories. However, the amount of deposited snow almost never corresponds to the amount of precipitation felt due to the concentration of snow on glaciers or to a snow blowing away from them. Increasing precipitation appearing through the moisture sublimation from the air usually accounts for less than 10% of a glacier's accumulation.

Contributions from avalanches to accumulation volume on valley glaciers usually does not exceed 10%, and it rarely reaches 20% , while small glaciers receive additionally up to 40% of the total volume of solid precipitation. Under especially favorable conditions this figure may exceed 100%. On average, the the amount contributed by avalanches on large valley glaciers amounts to 5%, while for small ones it is about 20%; this is, at least, three times less than the total contributed by snowdrifts .

Degrees of snowdrift and avalanche snow concentration on glaciers can be quantitatively expressed through a coefficient of concentration $\boldsymbol{k}$:

$$k = C/X_T = (F_1 + F_2)/F_1,$$

where $\boldsymbol{X_T}$ is a amount of solid precipitation; $\boldsymbol{C}$ is annual accumulation on a glacier; $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are snow and snow-less areas on the glacier basin. On typical corrie glaciers, the $\boldsymbol{F_1}$ area slightly exceeds the glacier area by the end of the ablation period. The larger the snow-less areas around a glacier, the greater a snow concentration on it. For any particular glacier, the coefficient of concentration is a rather stable value. It is equal to 1.5-2.0 at corrie glaciers, 1.4 at small valley ones, and 1.25 at great valley glaciers. It is under the unit at glaciers of flat tops and ice sheets since snow falling from the atmosphere is partly blown away by wind across the plano-convex surface of glaciers of this type.

Annual accumulation may be calculated for any point on a glacier as well as for its separate parts and over a glacier as a whole. In the first case, it is termed a specific accumulation and expressed in $g\ cm^{-2}$ or a water equivalent of a mass deposited.

Accumulation on a given glacier is characterized by its rate and altitude gradient. A rate of accumulation is a mass increment on a glacier for the time period considered. The vertical gradient of accumulation shows its change with altitude on a glacier; it is not regular since accumulation depends on a relief of the glacier surface and surrounding mountains. As a rule, maximal values of the accumulation are typical for the firn basin of a glacier, namely at its center due to the greatest precipitation occurring there , and near the back wall and along its sides owing to accumulation ofsnowdrifts and avalanching in those areas.

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Biographical Sketch

Vladimir Mikhailovich KOTLYAKOV (born in 1931) is a member of the Russian Academy of Sciences (elected in 1991). He is Director of the Institute of Geography, Russian Academy of Sciences. With particular interest in glaciology and physical geography in polar and mountain regions, he directed the twenty-year project resulted in the World Atlas of Snow and Ice Resources (published in 1997).

V.M. Kotlyakov participated in many expeditions. He worked and wintered in the Arctic, the Antarctica, at the slope of the highest summit of Europe, the Elbrus, headed the high mountain glaciological expeditions to the Pamirs.

The main theoretical results of V.M. Kotlyakov`s works consist in the elucidation of laws of snow and ice accumulation of the Antarctic ice sheet as well as ice sheets in general (1961), the snowiness of the Earth and its fluctuations within time and space (1968), the tasks and abilities of the space glaciology (1973), the application of isotope and geochemical methods to the study of the environment and its evolution (1982), the study of the past four glacial-interglacial cycles (1985 and further on). During the last years, V.M. Kotlyakov dealt with the global changes of the environment, geographical aspects of global and regional ecological problems, the problems of interaction between the Nature and society.

V.M. Kotlyakov is the vice-president of the Russian Geographical Society and the President of the Glaciological Association. In 1983–87, V.M. Kotlyakov was elected the President of the International Commission of Snow and Ice, in 1987–93, he was the member of the Special, and later Scientific, ICSU Committee of the International Geosphere-Biosphere Programme, and in 1988–96, the vice-president of the International Geographical Union. Now he is a member of the Earth Council.

V.M. Kotlyakov is elected a member of the Academia Europaea and the Academy of Sciences of Georgia, a honorary member of the American, Mexican, Italian, Georgian, and Estonian Geographical Societies.