CLASSIFICATION OF GLACIERS

Vladimir M. Kotlyakov
Institute of Geography, Russian Academy of Sciences, Moscow, Russia

Keywords: Glacier, glacier system, grounding line, iceberg, ice formation zones, ice cap, ice sheet, ice shelf, inland ice, mountain glacierization, outlet glacier

Contents

1. Introduction
2. Geophysical classifications of glaciers
3. Morphological classification of glaciers. Mountain glacierization
4. Polar glacierization
5. Interaction between glaciers and the ocean
6. Processes at a glacier bed
Glossary
Bibliography
Biographical Sketch

Summary

Glaciers are products of interaction between the land relief and climate. A geophysical classification is that glaciers are distinct according to their heat state and thermal regime below the active layer. H. Ahlmann isolated three classes of glaciers which are moderate, or warm ones, where their whole thickness, except the uppermost layers, is at the melting temperature of ice; polar glaciers which even in summer have negative temperature down to a great depth and have no melting; sub-polar glaciers in whose thicknessess negative temperatures dominate but in summer melting is possible. Morphologic classifications of mountain glaciers divide the whole glacier diversity into three groups which are glaciers of tops, slopes and valleys. For majority of mountain glaciers, their forms are directly determined by structures of surface topography. Reticular glaciers, i.e. transient type from a mountain to a sheet glaciation, are characterized by a complex of water-gap valleys filled with glaciers, and by glacier domes on a watersheds. Forms of ice sheet do not depend on land relief since it is conditioned by distribution of ice accumulation and discharge. Ice sheets are formed in regions where a snow line comes down to the level of lowlands, and sometimes (more rarely) on high plateau-form highlands. Ice sheets and domes, outlet glaciers and ice shelves are separated in a reticular glaciation. Morphology and movement of ice sheets are almost independent of its bed topography. Land ice sheets overlying bedrock above sea level, and "marine" ice sheets overlying continental shelves are distinguished in glaciology. The main ice runoff from ice sheets and domes occurs in outlet glaciers. A glacier of ice shelves is the continuation of a land ice sheet on the sea surface. Such glaciers are typical for regions with low (relative to the sea level) position of the equilibrium line, and now they are encountered almost only in Antarctica. Floating glaciers are continuously affected by sea tides; high tides cause an iceberg calving. Huge thickness of ice sheets makes a colossal pressure in their depths, and at deep levels their temperatures can reach melting point of ice. In Central Antarctica continuous

under-glacier melting reaches 3-5 mm per year. sub-glacial lakes exist here, and the largest is discovered in the region of the Vostok station.

1. Introduction

Glaciers in Nature result from interaction between climate and relief. Glaciers are mainly formed from snow precipitation but, partly, they consist of ice (for example, ice shelves). The ice may be present also in mountain glaciers resulting from freezing of melting and rain waters on a glacier surface, in crevasses and cavities inside a glacier. Thus, actually all types of natural ice are present in glaciers.

The first classification of natural ice, that is ice-I variant which is the only one occurring in Nature, was proposed by the Polish scientist A. Dobrowolski (1923). It was based on origin and petrographic structure of the individual types of ice. Dobrowolski distinguished two groups of ice rocks: the magmatic ones, i.e. formed after the freezing of water (floating and bottom ice, grained rime), and the sedimentary rocks (snow cover and glaciers).

The most advanced classification of natural ice suggested on the basis of petrographic principles is due to the Soviet glaciologist P.A. Shumskiy (1955) who analyzed about 30 types of ice rocks and classified them into three groups: congelation ice (from water basins and water streams, underground ice, ice rain, and partly hail and grains); sedimentary ice (snow cover); metamorphic ice (glacier ice).

Wherever glaciers are located, at the end of summer, we always see on their tongues a glazed ice, and in the accumulation area - firn, i.e. a transitional stage between snow and glacier ice. The name “firn” originated from the old German word “Firn”, for snow lying on mountains for a long time. It is true that snow transforms into firn gradually, and this process takes place most quickly in summer under the solar radiation effect and thaws. Under colder conditions it is the result of recrystallization and sublimation of water vapor. So, in their heads, glaciers usually have thick firn layers which are porous masses above a low permeable ice.

Many processes on glaciers are controlled by their heat regime. The upper layer of a glacier where seasonal temperature variations penetrate the glacier thickness is called an active layer. The bottom of this layer is a level where the amplitude of temperature variation is 500 times as small as on the surface. Its depth is 21-22 m of ice, and 15 m of firn. Penetrating the firn melting water overtakes and suppresses the cold wave propagating in the layer after the winter time. This reduces the active layer thickness down to 10 m. The heat regime of deeper layers of glacier is not influenced by the seasonal variations of temperature, and thus, represents its long-term heat regime.

2. Geophysical Classifications of Glaciers

Geophysical classification is a distinction among glaciers according to their heat state and thermal regime below the active layer. For the first time, such a classification was proposed by M. Lagally (1933). He divided glaciers into warm, cold and transitional. As the transitional type he defined such glacier whose upper part was cold while the lower one is isothermal. The glacier classification proposed in 1930s by H. Ahlmann is widely known. Three classes of glaciers were separated in this classification: glaciers of a moderate climate, or warm ones, where the temperature is equal to the ice melting temperature throughout the whole thickness, except the very upper layers; polar glaciers where temperatures are negative down to a great depth even in summer, and there is no melting; sub-polar glaciers are those inside of which negative temperatures dominate but in summer melting is possible.

Later on, in 1950s, the Soviet glaciologist G.A. Avsyuk distinguished five basic types of temperature distribution inside glaciers: 1) dry polar type, when temperature is below the ice melting point throughout the whole glacier thickness (Antarctica, Greenland, mountains of Central Asia above 6000-7000 *m*); 2) humid polar type where summer temperature rises above 0 °C and a little melting takes place, but the ice temperature inside the glacier thickness remains below average annual air temperature (the first type of periphery); 3) humid-cold type when the ice average temperature is higher than the air average temperature, however, both of them are negative, and the melting takes place in only the upper part of the whole thickness (glaciers of the Arctic islands and Patagonia); 4) marine type when zero temperature dominates throughout the whole thickness below the active layer (glaciers of the Caucasus, Alps, Alaska, Scandinavia, and others); 5) continental type when the ice average annual temperature is negative at all depths, although some warming-through takes place in the upper layers followed by melting (glaciers of the Tien Shan, Pamirs, the Canadian Arctic archipelago). Now, dry polar, marine and continental types of the temperature distribution inside the glaciers are the most wide-spread over the globe.

As our understanding deepens it becomes clear that within the same glacier, especially, if it reaches very large size, intensity and course of ice formation in different parts are different. This results in non-uniform structure of the firn-ice thickness and different rate of the firn transformation into ice. Variations in the ice-formation conditions on glaciers reflects the altitudinal zonality and allows separation of the ice formation zones.

By P.A.Shumskiy	**By A. Court**	**By C. Benson**	**By F. Mü ller**
Snow zone	Unmelting glaciers	Facies of dry ice	Zone of dry snow
Snow-firn zone	Glaciers with a surface melting and freezing of melting water	Facies of infiltration	Infiltration zone A (zone of saturation)
Cold firn zone Warm firn zone Firn-ice zone Zone of superimposed ice	Glaciers with melting water spreading throughout the whole thickness	Facies of saturation Water-firn sub-zone with runoff	Infiltration zone B (zone of snow slush) Zone of superimposed ice
Ablation area		Facies of ablation	

*Complete genetic names of zones by P.A. Shumskiy(see in the text.)

Table 1. Ice-formation zones

Several classifications of the ice-formation zones are known: A. Court (1957), C. Benson (1961), F. Müller (1962). The first of them is based on experience gained during investigation of glaciers in North America, the second one was on the basis of investigations in Greenland, and the last - on glaciers of the Canadian Arctic archipelago. However, the most perfect classification was developed by P.A. Shumskiy (1955) who has named zones according to dominant processes of ice formation. A comparison of the above ice-formation systems is shown in Table 1.

Alphabetic symbols used to characterize the zones are the following: X is annual precipitation sum; X_l and X_s are amounts of liquid (l) and solid (s) precipitation; m is the amount of melting; T_c is a storage of cold in glacier expressed by the equivalent layer of water which may be frozen due to this storage; M_r, M_i, M_{rj} and M_c are quantities of re-crystallization, infiltration, regelation and congelationl ice formed during a year; p is the volume of pores in an unmelted snow remainder.

1. Recrystallization (snow) zone. Here, $X = M_r$; $X_l + m = 0$. Melting is absent, ice formation takes place completely by means of subsidence and re-crystallization. The firn thickness is 50-150 *m*. The lower boundary which is named by Benson as dry snow line corresponds to the air average summer temperature of about -9 °C and average annual temperature of -25 °C. It is spread over the whole inner Antarctica higher than 900-1350 m above the sea level, in the northern half of Greenland ice sheet (higher 2000-3000 m) and on the highest peaks (at the Pamirs is higher 6200 m).

2. Recrystallization-regelation (snow-firn) zone. Here, $X = Mr + Mrj$; $X_c + m << p$; $X_l + m << T_c$. Melting takes less than 0.1 of snow accumulated during a year. Melting water freezes completely inside the annual layer, and ice formation takes place mainly by means of subsidence and re-crystallization. The firn thickness is 20-100 m. The lower boundary is called by Benson as saturation line since saturation of the whole annual snow layer takes place at this level. It is present at the periphery of the Antarctic ice sheet (between 500 and 1000 m above the sea level), in the southern part and at the periphery of the Greenland ice sheet (at altitudes 2000-3000 m in the south, and 1000-2000 m in the north), at individual island ice sheets and mountain peaks (at the Pamirs is higher 5800 m).

3. Cold infiltration-recrystallization (cold firn) zone. Here, $X = M_i + M_r$; $X_l + m < p$; $X_l + m < T_c$. The volume of melting water is sufficient for water yield from the annual layer. It comes into the lower layers where it freezes. At large inclinations it partially goes into a runoff (sub-cold zone). Melting takes from 0.1 to 0.5 of the annual accumulation. The firn thickness with thick ice inter-layers is only 10-20 m, the glacier temperature is negative. About 2/3 of ice formation takes place due to infiltration, and only about 1/3 due to subsidence and re-crystallization. It is widely spread in mountains with continental climate and on island ice caps, but on continental ice sheets it occupies a thin edge belt.

4. Warm infiltration-recrystallization (warm firn) zone. Here, $X \geq M_i + M_r$; $X_l + m = T_c$. The cold storage is not sufficient to freeze the melting water; its volume is equal to 0.4-0.7 of the annual accumulation. Intensive runoff takes place in this zone, and the ice formation takes place equally due to both the infiltration freezing and subsidence with recrystallization. The firn thickness with thin inter-layers is 20-40 m, the glacier temperature is close to zero. This zone is widely spread in mountains and on island ice caps with the marine climate.

5. Infiltration (firn-ice) zone. Here, the melting water constitutes more than 0.5 of the annual accumulation, i.e. the volume of pores in the annual remainder, but the firn retains due to accumulations of preceding years in the glacier upper zone, or during the past colder and snowy years. The firn thickness does not exceed 10 m, often, it is less than 5 m, and ice formation is mainly infiltrational. This zone always infringes from below the other firn zones or exists independently due to the climate changes during formation or disappearance of these zones. At present, it is widespread, may move down across the equilibrium line into the ablation zone in the case of the firn initial large thickness, fast motion and great ice inclinations, specifically under intensive accumulation.

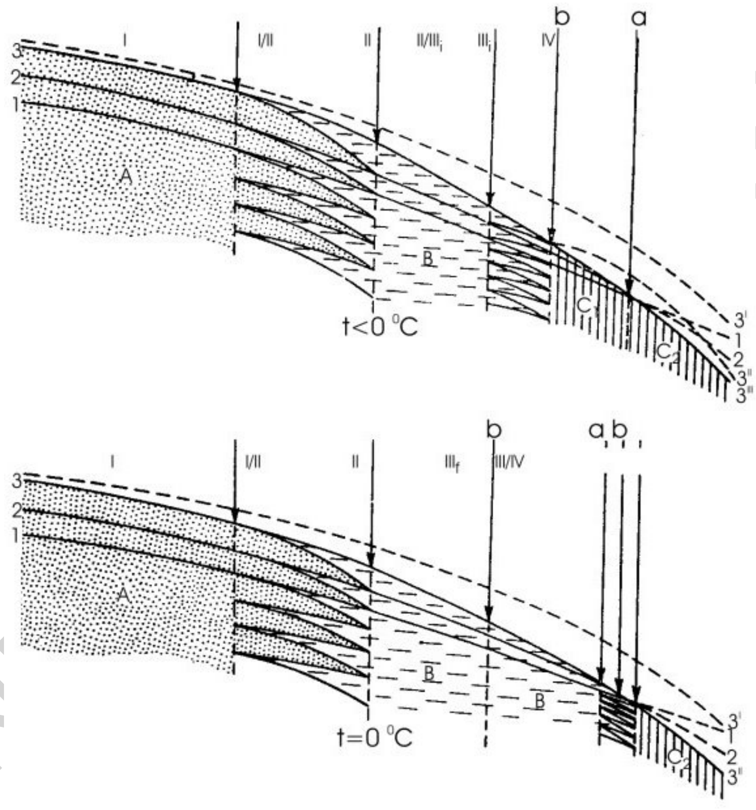

Figure 1. Ice formation zones and the surface-layer structure of a stationary glacier (by P.A. Shumskiy) in dry cold regions (above) and in relatively warm humid regions (below):
1 - recrystallization, *II* - cold infiltration zone, *III$_i$* - infiltration-congelation zone, *III$_f$* - warm infiltration zone, *IV* - ablation area. Boundaries: *a* - equilibrium line, *b* - firn line, *c* - isotherm of 0 °C at the depth where the annual temperature variations are damped. The surface-layer structure: *A* - snow, re-crystallization firn and ice, *B* - infiltration firn and ice, *C$_1$* - superimposed ice, *C$_2$* - deep-laid ice. Boundaries of layers: *1, 2, 3'''* - for three last years of the accumulation (melting - dashed line) at the end of summer, *3'* - highest altitude of the snow surface for the last year. The layer thickness is shown in the scheme approximately; scale along the vertical in the zones *I* - *IV* is different.

6. Infiltration-congelation, or ***zone superimposed ice.*** Here, $X > M_i + M_c$; $m < T_c + X_s$. All the pores of the annual remainder are filled with the infiltration ice. Melting exceeds 0.5 of the annual accumulation. The cold storage is greater than it is necessary for freezing infiltration over the total volume of the pores. The ice formation takes place completely by way of infiltration. It is located between the firn and the equilibrium lines. This zone exists at small inclination of the surface, low accumulation, small speeds of the ice flow, i.e. in continental climate.

Several zones of ice formation may occur on a large glacier or an ice sheet. They form regular sets depending on the degree of continentality of the climate (Figure 1).

-
-
-

Bibliography

Bennett M. R. and Classer N. F. (1996). *Glacial geology: ice sheets and landforms*. Chichester: Wiley. [Review of glacial geological activity.]

Drewry D. J. (1983). *Antarctica. Glaciological and geophysical folio*. University of Cambridge. [Set of maps, showing morphology and internal regime of the Antarctic ice sheet.]

Hughes T. J. (1997). *Ice sheets*, 343 pp. New York: Oxford University Press. [Proposed theory that Quaternary ice sheets trigger abrupt global climate change by advancing and retreating rapidly over large areas.]

Williams R. S. and Hall D. K. (1993). *Glaciers. Atlas of satellite observations related to global change* (ed. R. F. Gurney, J. L. Foster and C. L. Parkinson), 401–422. Cambridge: Cambridge University Press. [Some satellite images giving representation of different types of glaciers.]

World Glacier Inventory. Status 1988 (1989), 498 pp. IAHS – UNEP – UNESCO, World Glacier Monitoring Service. [Information about national glacier inventories compiled by 1988.]

Zwally H. J. (1989). Growth of Greenland ice sheet: interpretation. *Science*, **246**, 1589–1591. [Explanation a present-day positive mass-balance of the Greenland ice sheet.]

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). He 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 his works consist in 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 for four glacial-interglacial cycles (1985 and further on). During the last years, he 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. He is the vice-president of the Russian Geographical Society and the President of the Glaciological Association. In 1983–87, 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, in 1988–96, the vice-president of the International Geographical Union. Now he is a member of the Earth Council. He 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.