INTERACTION BETWEEN GLACIATION AND CLIMATE

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Summary

Snow cover, sea ice and glaciers are a unified natural system that is in permanent interaction with the climate. The heat of ice crystallization and that of melting are the most powerful factors of heat redistribution on the Earth. A third of the total balance of the Earth's external heat circulation is used for ice phase transformations. Large losses of energy over the snow cover causes the air temperature to drop not only directly over the snow but in the whole low layer of the troposphere. In North America and Eurasia, the system of general circulation in the atmosphere causes the cold air masses to move in a Southeastern direction, and thus it promotes the cooling of moderate latitudes. The direct cooling effect of snow upon the troposphere amounts to about 2.5 ^{o}C due to the albedo mechanism and 1.2 ^{o}C due to expenditures for melting. The sea ice cover is very stable to external impacts. For this reason, the present climate is stable, and it is not able to change for a short time even under active anthropogenic impacts, since the ice regime of the Arctic Ocean can be changed only if the fresh water balance in the Ocean is broken. Totally, glaciers on the land reflect into space about 5% of the Earth's total reflection. Due to the Earth's albedo increasing by 2% per summer half-year and by 1% per year (from 0.29 to 0.30), the ground air layer is cooled by approximately 1 ^{o}C, and by 1^{o} more due to the heat loss through turbulent fluxes. Thus, the total cooling caused by modern glacierization is equal to 2 ^{o}C. During the last glacial epoch, when the total glacier area increased by four times, and duration of the seasonal stay of the snow cover and sea ice greatly increased and the planetary albedo increased still more. As a result, in the midst of the glacial epoch the mean global temperature dropped additionally 3^{o}. If the global temperature rise will amount to 2-3^{o} by the middle of the 21st century, then the ocean level will probably rise by 0.5-1.2 *m* due to the ice melting and heat

expansion, and with the possible disintegration of the West Antarctic ice sheet the level can be increased by still several meters more.

1. Introduction

Snow cover, sea ice and glaciers form a unified natural system, interacting with the climate. The heat of crystallization that is released during the formation of atmospheric ice, as well as the melting heat that is absorbed under the ice particles' precipitation to the Earth's surface and transport into lower latitudes, are the most powerful factors of heat redistribution on the Earth. The heat expenditures for the annual melting of all snow and ice accumulated during a year reach approximately 0.2% of the whole flux of the solar radiation absorbed by the Earth, while the ocean heat expenditures for melting icebergs and the destruction of ice shores are commensurate with the river "heat runoff" into the ocean. One third of the whole balance of external heat exchange on the Earth is spent during ice phase transformations.

2. The global climatic role of snow cover

When looking at the Globe from space, the eye immediately notices huge areas occupied by snow as well as sharp irregularity of its occurrence in the Northern and Southern hemispheres (Table 1). There is much more of snow in the Northern Hemisphere where in winter it covers the two largest continents, while in the Southern Hemisphere a similar expansion is prevented by the oceanic spaces. Since winter and summer in the Northern and Southern hemispheres come at opposite time, the snow covers alternatively the North or extreme South of the Earth. The total area of snow cover (millions of km^2) at the end of the winters of both hemispheres, i.e. approximately in February and August, changes as follows:

At the end of the Northern winter, i.e. in February, the snow covers 19.2% of the whole globe area, with 31% of this coverage in the Northern Hemisphere area and 7.5% in the Southern . Quite another ratio is formed in August. During this time, snow covers only 9.2% of the whole globe, while on the hemispheres the pattern is the following: 14% of the area of the Southern Hemisphere is under snow, and only 4.3% of the Northern one. Thus, during a year, in the Northern Hemisphere the snow area changes by a factor of 7.2, while in the Southern it changes by less than a factor of 2. All these figures characterize the average conditions of current snowiness.

	Northern Hemisphere	Southern Hemisphere
On the land	75	18
On the sea	23	29
Totally	98	47

Satellite data allows the estimation of snow cover sensitivity to the temperature changes on the Earth. It turns out that, in the Northern Hemisphere, when the near-surface air temperature rises by 1°C, then the snow cover area reduces by 3.5-5.1 millions of km^2. It corresponds to a regression of the south boundary of the snow cover by about 2° of latitude.

Snow cover	Area, mil km^2	Average accumulation, $g \cdot cm^{-2}$	Mass of seasonal snow, 10^{11} tons
Northern Hemisphere			
Permanent on a land	2	25	5
Temporal on a land	59	14	83
On permanent sea ice	9	10	9
On seasonal sea ice	9	12	11
Southern Hemisphere			
Permanent on a land	14	16	20
Temporal on a land	2	15	3
On permanent sea ice	5	18	9
On seasonal sea ice	15	20	30
Total	115	15	173

Table 1. Area and mass of the snow cover annually formed (average figures)

In the 1870s, the well-known Russian climatologist A.I. Voeikov stated several important concepts testifying to the influence of snow cover on the climate:

- the surface temperature of the snow layer is usually lower than that of the snow-free soil and the ground air layer;
- owing to the strong cooling of the air over the snow surface, a temperature inversion is formed;
- the cooling influence of snow cover is especially strong on plains and in surface depressions;
- increased atmospheric pressure is noticeable over the cold snow surface even on an average over many years;
- due to great heat expenditures for snow melting and evaporation, the May month in middle latitudes is much colder than September, and this difference increases in very snowy regions.

The validity of these ideas was proved by the wide observations from the space, which allowed obtaining of simultaneous information about the snow on huge territories and showed its planetary role for the Earth’s climate and Nature. Existing for a long time on great areas, the snow cover does reflect not only the climate fluctuations, but it also influences itself upon the atmosphere circulation. In such a way, it serves as both an index and a reason for the climate changes.

Since the snow surface temperature can not be higher than 0°C, the air convection warming is greatly decreased or totally absent; because of a high albedo, absorption of the solar short-wave radiation is reduced by about three times. If we take the mean annual area of snow and ice cover in both hemispheres equal to 62 million km^2, and the radiation striking a unit of the area is equal to half of the mean global sum, then, under permanent cloudiness and other rough assumptions, it turns out that the solar radiation income decreases due to snow cover by $13 \cdot 10^{19}$ $kJ \cdot year^{-1}$, or by more than 4% of the radiation absorbed by the whole planet.

Absorption (during snow evaporation and melting) and release (during water condensation and freezing) of significant amount of the heat from the water phase transformations continuously proceeds on the snow surface. It results in a heat exchange between the air moving and the snow thickness that smoothes sharp temperature fluctuations. Under advection of warm air masses the rising air temperature is quickly stopped as the heat is absorbed by the snow, strongly cooled by a preceding cooling. Strong cooling, on the other hand, is reduced by the heat storage preserved within the snow thickness.

In spring, the snow cover weakens thaws and delays the air heating; evaporation from the snow cover retards the course of natural processes, and, after the appearance of thawed patches, air begins to heat more quickly. The phenomena of snow inversions are typical for the springtime when the airflow moving over the snow is cooled because the air layer, laid over the snow cover, expends its heat on snow melting. This results in a drop in air temperature in this layer as compared to the overlying layers. However, the humidity of the lower atmosphere layer sharply decreases over the snow, actively melting, and that promotes its further heating. In the long run, snow disappears, and the character of the heat exchange between the air and the Earth's surface immediately changes.

The effect of snow cover upon the atmosphere circulation is expressed in expanding and stabilization of the circulation anomalies, causing unusual weather features. Snow cover exerts a great influence on the transparency of air, increasing it, since the snow cover formed prevents the wind from lifting mineral and other particles from the land surface. As a result, in snowy regions the air is particularly transparent and clear, and that favors a greater income of solar radiation.

The surface becomes colder than the air immediately after a snow cover has been laid. In the course of winter, this difference increases, most of all in January and February, when a mean air temperature minimum on the surface and in the air differs by 3-4°C, and the absolute minimum may differ by 5-10°C.

Great energy losses over the snow cover cause the air temperature to drop not only over snow, but also throughout the whole lower layer of the troposphere. Such conditions are formed over vast land spaces in middle and high latitudes, particularly in Siberia, in the northeast of North America and in the Antarctica. It results in the formation of very cold air masses under a weak wind and clear sky. In their lower 1-2-km layer, the air temperature rises with altitude. Being a part of the system of general atmospheric circulation, these masses move southeasterly and promote cooling of the middle latitudes.

The cold, dense air layer formed over the snow surface hampers air mass heating and, therefore, a stable state of the atmosphere is retained here for a long time. If some clouds are formed under these conditions, then a flux of diffuse radiation is 50% greater over the snowy territory than over bare ground. Usually, a multiple reflection occurs between snow and the cloud base that increases the energy coming to the snow cover.

Snow cover plays a significant role in the formation of both the Siberian anticyclone in Eurasia and the Canadian one in North America. As the snow cover boundaries shift southward, the Arctic air masses spread farther to the south, the anticyclone area is expanded, and the cyclone paths are displaced to the south. In both Eurasia and America the cyclones often move along the snow cover boundary and bring new snowfalls. Fresh snow increases the snow cover's drying and cooling role and favors the spreading of snow to the south. This is one of several natural mechanisms characterized by great constancy, owing to thespreading of seasonal snow cover.

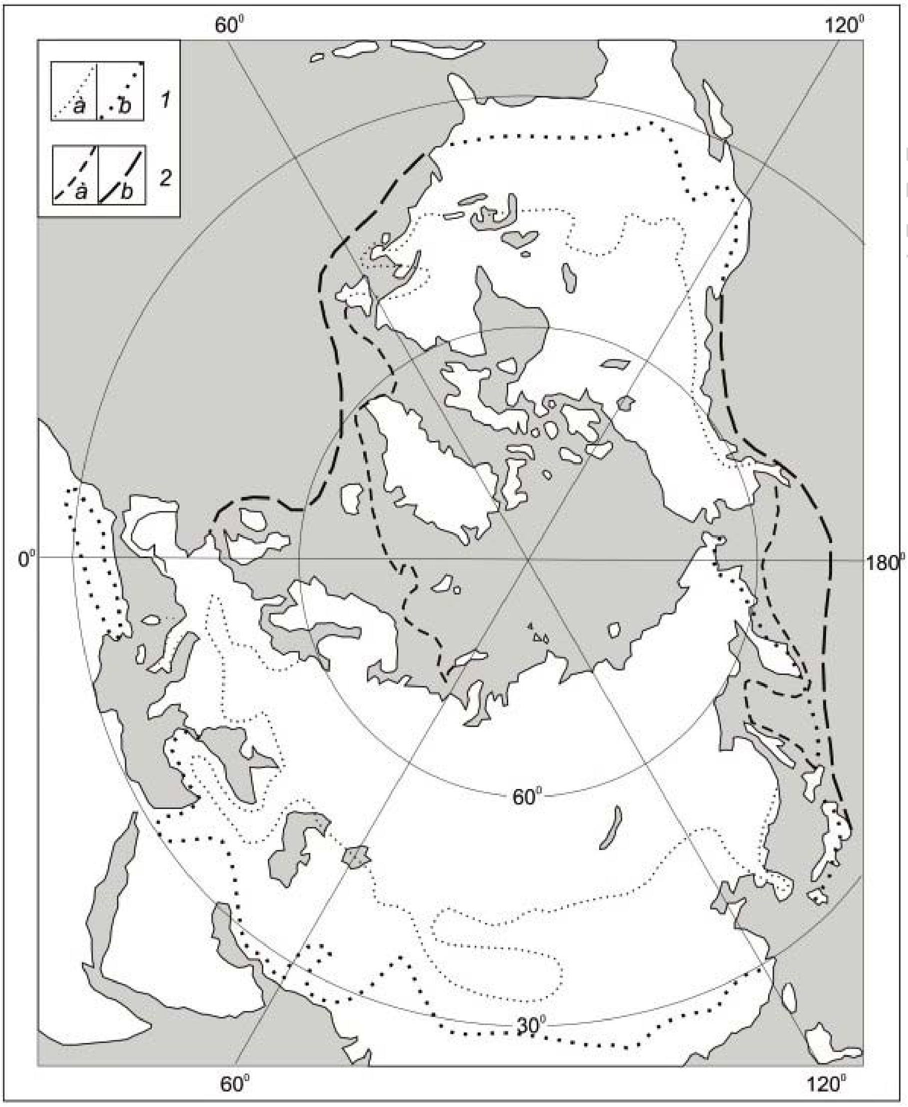

Figure 1. Distribution of seasonal snow cover on the land and sea ice in January 1980 (1) and during the winters of the last glacial epoch 18, 000 years ago (2)

Snow cover plays an important role in the formation and development of glaciers as well as in the whole existence of glacierization. It is evident that cold and snowy periods preceded and then accompanied the glacial epochs, and feedbacks, inherent to any snow cover, played a great role in the mechanism of the origin and drgradation of glacierization. Any long-lasting global cooling causes the growth of the area and duration of snow cover, and, thus, increases the planetary albedo and favors further cooling. On the other hand, if the snow cover on the Earth is reduced, the planetary albedo decreases and causes increased warming.

In the Pleistocene, winter snow cover undoubtedly occupied much greater areas in the Northern Hemisphere on both land and sea (Figure 1). During the Quaternary, snow covered up to 35% of the Northern Hemisphere, and up to 24% of the Southern Hemisphere, while respective figures for our epoch are equal to 30 and 14%.

In the global climatic system, the snow cover is a result of atmospheric circulation, but, in its turn, the snow itself exerts a certain impact upon this system. Even very small fluctuations in the surface mean temperature on the Earth are enhanced by the action of the feedback between the snow coverage and the planetary albedo. It is difficult to separate the global climatic role of the snow cover from its influence upon the climate of continental ice sheets; one should remember that the glacial periods on the Earth always were also periods of increased snowiness.

The direct cooling influence of snow on the troposphere amounts to about 2.5°C due to the albedo mechanism, and to 1.2°C because of the heat expenditures for snow melting. Total cooling is close to 4°C, and together with summer snow-free glaciers, it is about 5°C, which is comparable to the global cooling in the Quaternary as compared to the present-day state.

3. Sea ice as a part of global glaciation

In the current epoch ice covers 23.74 million km^2, or 6.6% of the World Ocean area on average each year. Of that amount, 12.65 million km^2 is accounted for in the Northern Hemisphere, and 11.09 million km^2 is in the Southern. However, the ice distribution changes markedly through seasons: from 8 to 16 million km^2 in the Northern Hemisphere, and from 3 to 19 million km^2 in the Southern. Maximum and minimal ice progress in these hemispheres occurs at opposite times of the year: March and September. The amplitude of seasonal variations in the Southern Hemisphere is twice that in the Northern. It is connected with the “closed” position of the sea ice in the Arctic and “open” position in the Antarctic, and indirectly testifies to the greater stability of floating ice in the Northern Hemisphere.

More than 33 thousand km^3 of sea ice is formed annually, including about 13 thousand km^3 in the Northern Hemisphere, and 20 thousand in the Southern. On the whole, on the North of the planet, the volume of sea ice changes from 20 thousand km^3 at the end of summer and in autumn, when only pack ice remains on the sea surface, and up to 35 thousand km^3 in spring, when the seasonal ice reaches its maximum extension. In the South, the respective volumes of sea ice change from 7 to 30 thousand km^3.

In different regions of polar seas, the ice cover duration is not the same: it varies from several months to many years. However, the average duration of ice in the World Ocean only a little exceeds 1 year: in the Northern Hemisphere it is equal to 1.3 years, while in the Southern it is 0.8 of a year.

In the 20th century, the amount of ice in the Arctic Ocean was the largest at the end of the 1920s, but at the end of the 1930s, 1940s and at the beginning of the 1950s, the ice area in the Arctic was reduced by approximately 1 million km^2 (Figure 2). The warming of the Arctic has arrived, and the ice coverage of the Arctic seas is drastically reduced. For the last 100 years, the course of temperature and ice coverage of the Central Arctic indicates that a change of a mean winter temperature by 5°C causes almost double the change in the ice volume, and the sea ice area changes by 10-15%, or by 1 million km^2. Under present conditions, a small change in the climate can cause significant fluctuations of the ice volume in the Arctic basin, and in this case, both reduction and growth of the ice cover are equally probable.

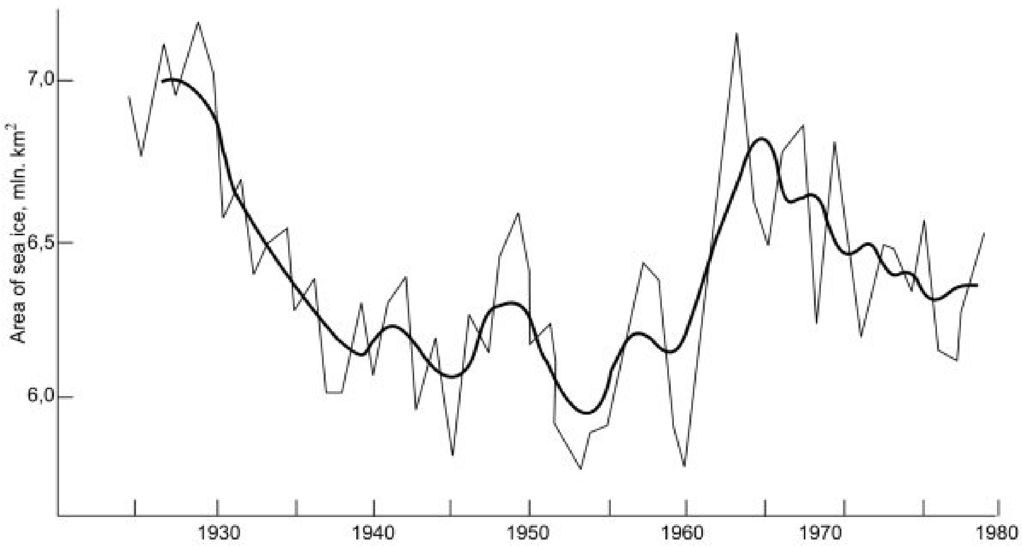

Figure 2. Area of ice in the Arctic ocean in the second half of August for 1924-80. Thickened line is drawn from data averaged over moving five years

There is still no unambiguous answer to the question of whether the Arctic sea ice is stable or unstable, whether it will be regenerated or not in the case of its destruction through natural or artificial causes. But, projects of influence upon the Arctic ice aimed at improvement of the climate and the navigation conditions have been repeatedly proposed. It was suggested, for example, to reduce the reflective capability of the ice by a special seaweed, growing in the ice, and, thus, to favor melting of the ice cover. In the middle of our century, the project of building a pump station in the Bering Straits became known, aimed at pumping water from the Arctic Ocean into the Pacific, which could enhance the inflow of warm water from the North Atlantic into the Arctic, and thus, would accelerate melting of the ice. Both these projects were never realized.

If the Arctic sea ice could be destroyed, then near the Pole the mean air temperature would rise during the warm period from -2 to 2°C, while during the cold period to would go from -29 to -3°C. As we can see, this difference is great, but it is close to the conditions under which ice formation proceeds.

However, the origin of ice in the ocean depends mainly on the upper desalinated layer of the sea water. Therefore, given the contemporary structure of the surface waters of the Arctic Ocean, the once destroyed polar sea ice would be very quickly regenerated to its earlier size. Only with the removal of the desalinated layer would the heat flux from the ocean depths go to the surface, and the conditions would be formed that would prevent the regeneration of the ice cover.

It is clear now, that climatic conditions on the Earth are significantly connected with the sea ice cover, which, in its turn, is very stable to external effects. Therefore, we may talk about the stability of the present climate, which can not be changed in the short term even under active anthropogenic impacts, since the ice regime of the Arctic Ocean can be changed only if the fresh water balance in the ocean is broken.

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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 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, 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, 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.