SURVIVAL OF DEVELOPED INTRAGLACIAL WATER CHANNELS IN COLD AND TEMPERATE GLACIERS

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Abstract

A numerical model, simulating the evolution of an intraglacial water channel in a glacier, was developed. It works in cylindrical geometry, therefore the calculations are very fast and the accuracy of the results is very high. Numerous field observations show that a typical large water channel in a glacier consists of the nearly vertical wide part upstream (moulin, shaft) and the subhorizontal narrow channel deep in the ice. According to the results of the modeling based on this approach, such developed channels tend to become equilibrium in size. Combining this "typical channel" scenario with the winter scenario (without water), we held multi-year numerical experiments. Such long-term modeling showed that ice depth is more critical than ice temperature for a channel to survive till the next melting season.

Выживание развитых внутриледных каналов с водой в холодных и теплых ледниках

Предложена числовая модель, моделирующая развитие внутриледного канала с водой, которая работает в цилиндрической геометрии, поэтому вычисления осуществляются очень быстры, и точность результатов высока. Многочисленные полевые наблюдения показывают, что типичный крупный канал с водой в леднике состоит из почти вертикальной широкой части в верхней части (ледниковый колодец, шахта), превращаясь в субгоризонтальный и узкий канал глубоко во льду. Согласно результатам моделирования, основанного на этом подходе, такие развитые каналы стремятся стать равновесными в размерах. Комбинируя этот сценарий "типичного канала" с зимним сценарием (без воды), мы проводили многолетние числовые эксперименты. Такое долгосрочное моделирование показывало, что для выживания канала во льду до следующего сезона таяния глубина расположения канала во льду более существенна, чем температура льда.

Introduction

The water flowing on the glacier surface and penetrating into the inner and subglacial parts makes a complicated channel network, consisting of surface streams, moulins (vertical shafts, ponors), intraglacial pressurized or open conduits, and subglacial tunnels. The question of where and how water circulates within glaciers is of considerable interest from various points of view (Röthlisberger, 1972). Knowing the structure of a glacial drainage system and the parameters of the water flowing through it, we can understand glacier dynamics, inner ablation, outflow hydrograph and other hydrological processes. It is also helpful for water resource use planning in glacial regions, forecasting of outflow hydrograph during ice-dammed lake outburst and so on. Glacial tunnels and shafts are also subjects of high interest of cavers and speleologists, who directly penetrate into the inner parts of glaciers. Comparing to rock (limestone, gypsum, etc) caves, glacial caves are very changeable and short-lived, but it is supposed that the development of rock caves is very similar to that of glacier cavities. Therefore studying of glacial channels can also help better understanding of many speleological problems.

During intensive ice melting, many small and large streams flow on the surface of glaciers, and mostly penetrate into the ice through moulins or fissures. Development of water channels in glaciers depend on many factors: channel form and size, water temperature and discharge, and so on. It is known that glacial channels can exist not only in the warm season but also in winter period when there is little melt-water flowing in them. In addition, there are observations of water channels in cold glaciers. Therefore, for comprehensive describing the problem, we also have to take into account such parameters as ice temperature, and ice and water pressure. Using a numerical approach, we tried to clarify the behavior and survival conditions of typical glacial water channels.

Physical background

As flowing downstream, water loses its potential energy. Strictly speaking, first of all the potential energy of flowing water tends to change into kinetic energy. But due to friction forces, the kinetic energy (water flow velocity) almost never reaches significant values. Even in real channels with complicated forms, in which water flow velocity can change along the conduit, the variations of the kinetic energy along the channel is considered to be negligible. Thus, in this work we supposed that all potential energy ΔE_p transfers to heat and is the reason of water warming. This heat, in its turn, spends for the water warming ΔE_w and the heat exchange with the ice ΔE_{i-w} (as we consider only intraglacial channels, heat exchange with the air and the influence of the solar radiation is not taken into account):

$$\Delta E_p = \Delta E_w - \Delta E_{i-w} \qquad (1)$$

In order to know the change of a channel, we have to calculate the rate and direction of phase change on the ice walls. The heat transfer ΔE_{i-w} from the water to the ice spends for ice warming ΔE_i and melting (or freezing) ΔE_{melt}.

$$\Delta E_{i-w} = \Delta E_{melt} + \Delta E_i \qquad (2)$$

The heat exchange between ice and water can be calculated by knowing the temperature difference and the heat transfer coefficient, and the heat flux into the ice can be found out by knowing the temperature distribution in the ice.

Thus, from (1) we find out the water temperature, and from (2) we calculate melting or freezing rate on the channel walls, that together with ice creep rate calculation allows us to find out the evolution of the channel. Detailed theory on this subject can be found in (Isenko, 2005; Isenko *et al.*, 2005).

The numerical model

We developed a 2-dimentional cross-sectional model, with which changes in the cross-section form at some particular points of a channel can be calculated. This cross-sectional model calculates ice temperature distribution around the channel, heat exchange between ice and water, and ice creep rate. For this we should know water temperature, water flow velocity, water and ice pressures, channel slope and some other parameters. Finally, on the basis of these calculations, we find out new ice/water border form and position.

Although several numerical models were developed (including the models for a cross-section of complicated form (Isenko, 2000; Isenko *et al.*, 2001), only the one dealing with channels of cylindrical geometry is considered in this work. The simulations with this model are very fast and the accuracy of the results is very high. Varying input parameters we conducted a set of model experiments, corresponding to the most typical situations

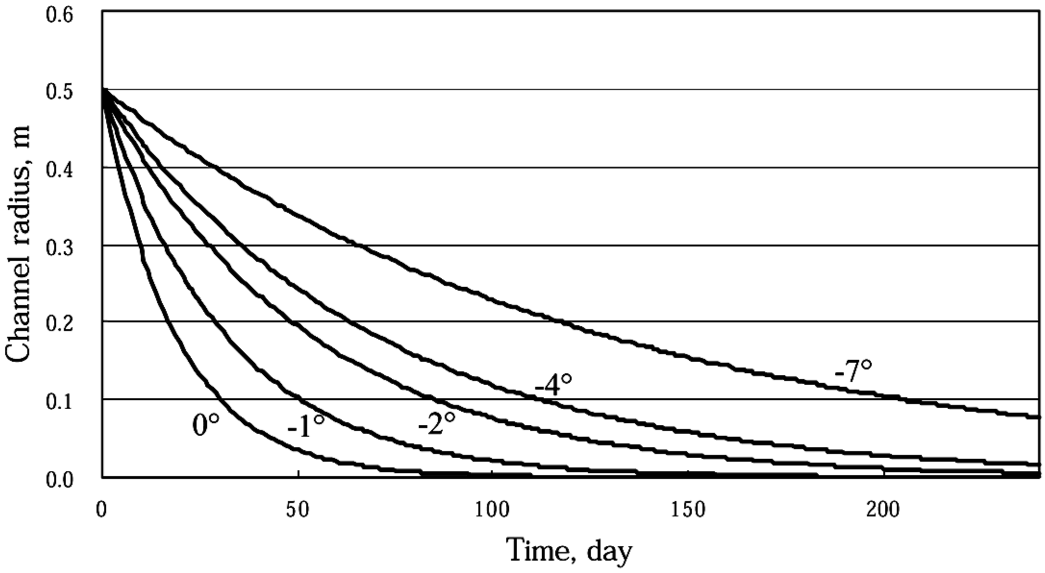

Fig. 1. Channel development without water («winter scenario») for different ice temperatures. Channel situated in ice at depth 150 m

Results of numerical modeling

Winter scenario

In the accumulation season, usually there is almost no water within glaciers because of zero melting due to weather. In polar glaciers the water, remained in the ice, will freeze off. In temperate glaciers such water can survive until the next season and some small water discharge can exist because of the geothermal heat and frictional energy dissipation in the ice. Nevertheless, the most of the caverns in ice are empty in winter. If such caverns are deep in the ice, the contraction due to the overburden ice pressure will arise.

The curves in Fig. 1 represent the change of the radius of an empty cylindrical cavern during 270 days (nine months) that should be thought as one winter season. The cavern is 150 m deep in the ice and the initial radius is 0.5 m. In all cases corresponding to the ice temperature above –4ºC, channel almost completely collapsed before melting season began. Although the channels in cold ice have high chances to survive. On the other hand, the channels in cold ice have high probability to cease due to freezing after water flowed into them. The question of which factor is more significant for surviving of a channel throughout many years is studied here.

There is always ice creep unless the channel is near-surface or the pressures of ice and water are strictly the same. The calculation of the ice creep is included in all models below.

Developed channel: «typical intraglacial channel» model

Typically, the upper part of a glacial drainage system consists of wide non-pressurized channels, usually vertical (shafts, moulins). Lower parts are narrower because of ice contraction, completely filled with water (pressurized) and usually subhorizontal. Such typical geometry is confirmed by numerous observations and glacio-speleological reports. That is why we called it «typical intraglacial channel».

The main point of that model is that the water discharge depends on outer conditions, rather than the channel size, and some water level should be in the upper part of the channel (Fig. 2). The higher the water level, the higher the water pressure gradient in the channel, so that more water can flow into it. Here we can see negative feedback mechanism that should put the system in a stable equilibrium state. When the channel is narrow (Fig. 2a), water level and consequently water pressure is high, so that ice creep rate is low and channel tends to grow, and vice versa, when the channel is wide (Fig. 2b), water level and pressure drops, and the channel grows due to low rate of the ice creep.

If the channel is too narrow so that even at the maximum level water cannot drain through it completely, overflow event occurred. We should say that the upper part of the system shown in Figure 2 is not obviously the glacier surface. It can represent some level in the ice, from where the single trunk channel begins.

Therefore it does not mean that overflow should occur on the surface of a glacier.

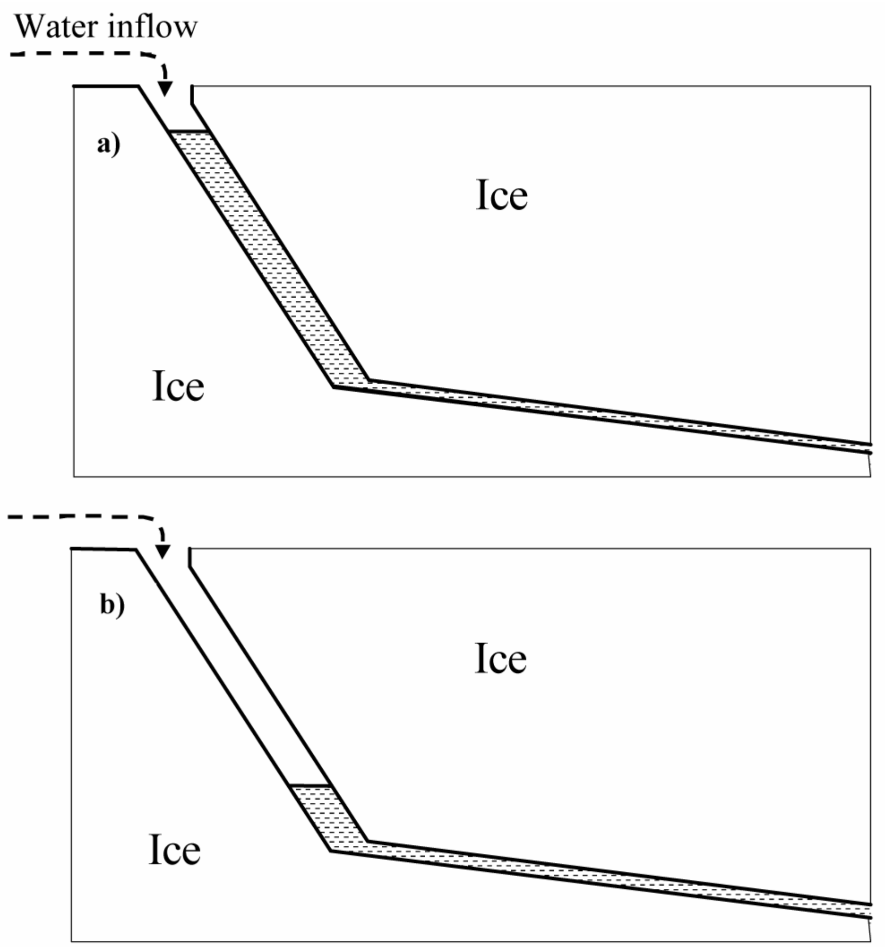

Fig. 2. Two situations with a «typical intraglacial channel»: a) narrow channel (or high water discharge) – high water level, b) wide channel (or low water discharge) – low water level

The graphs in Fig. 3a confirm our assumption that in most cases the channel is in equilibrium. Development of channel with slope 0.5º, length 2000 m and with different initial radiuses in temperate ice is shown in Figure 6-10a for 50 m depth. If the initial size of a channel is large (the top curve) water level and water pressure are very low in it. Subsequently, the channel starts shrinking quickly in spite of melting on the ice walls of the channel. As becoming narrower, water level and consequently water pressure rises, that cause the creep rate to lower until the equilibrium between creep and melt is reached.

Narrower channels grow until equilibrium, because the water pressure at the initial moment is very high and ice creep is almost absent.

If the channel is very narrow at the initial moment (two bottom curves), overflow event occurs causing decrease in discharge of the water flowing into the channel.

That is the reason why the growth rate of the channel is very slow at the beginning. The channel can even freeze off if the ice is cold (Fig. 3b), but if the initial size is not very small, the channel tends to be in the equilibrium even in cold ice.

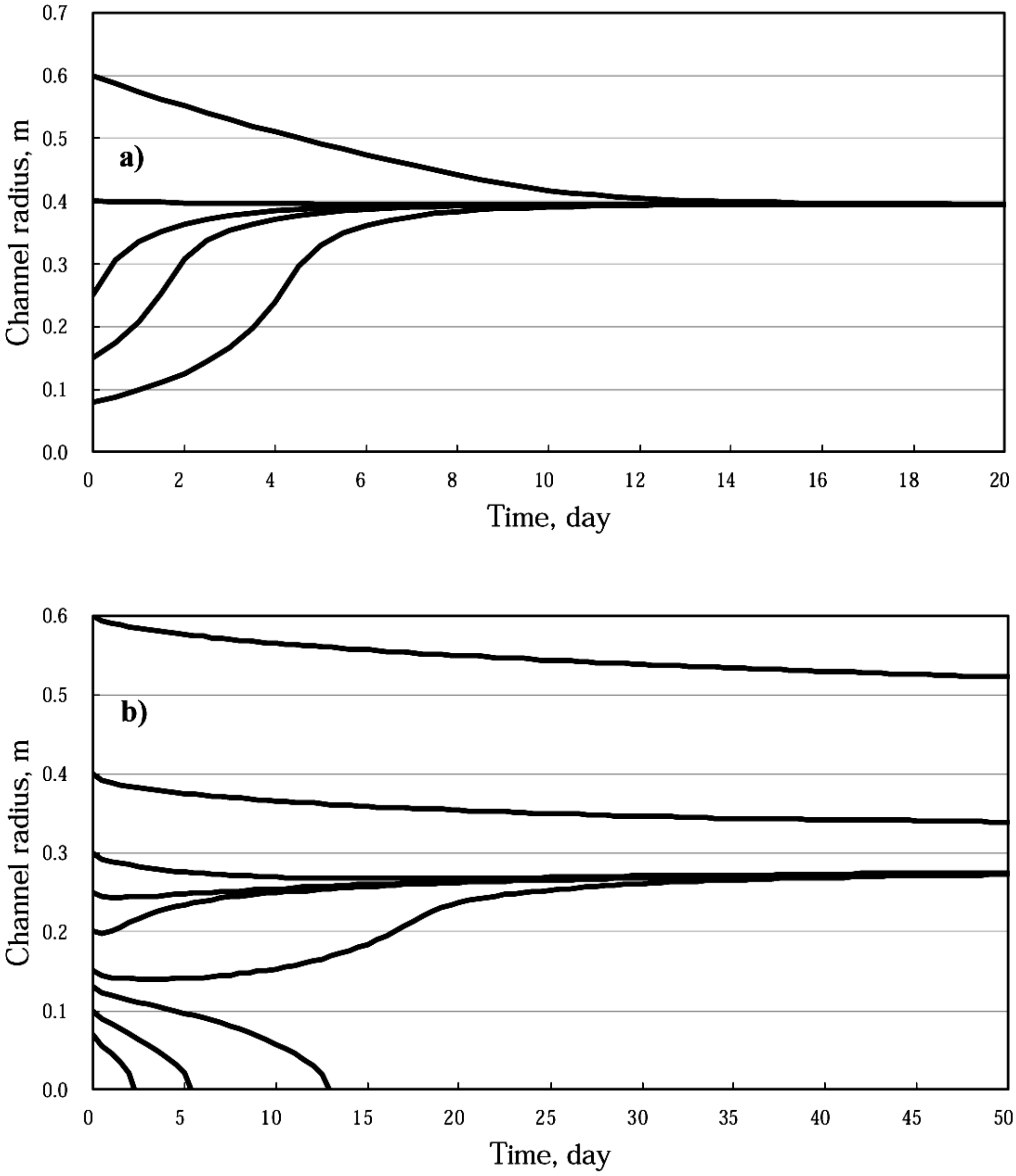

Fig. 3. Development of channels under the conditions of "typical intraglacial channel" model for different ice temperatures. Maximum water discharge 0.3 m^3/s, depth in ice 50 m, slope 0.5°, length 2000 m, ice temperature: a) 0°C, b) -5°C

Long-termed scenario

To clarify the question of how channels evolve throughout several years and what are the conditions for their survival through a long time, we combined together «winter» and «typical intraglacial channel» models. One year was divided into two intervals: eight months of absence of any water and four months with peak-like water discharge: it linearly increases from zero at the beginning of the ablation season to the maximum and than decreases to zero at the end of the ablation season (upper part of Fig. 4). Each of these time intervals is processed by, correspondingly, «winter» and «typical intraglacial channel» models.

The results of numerical experiments on development of a channel with slope 0.5º, length 2000 m and maximum water discharge 1 m^3/s in ice of different temperatures are shown in Fig. 4. Simulations start from the beginning of ablation season. During the first four months channels grow or shrink depending on the conditions. After water ceased from the conduits, they started to shrink like illustrated in Fig. 1. At the beginning of the next ablation season channels grow or decay depending on temperature and depth. For any set of simulations like in Fig. 4, we can define one critical point, on which the survival of channels depends. These conditions are summarized in Fig. 5 in the [ice temperature, ice depth] coordinates. As we can see, depth in ice is more critical than ice temperature for a channel survival till the next melting season.

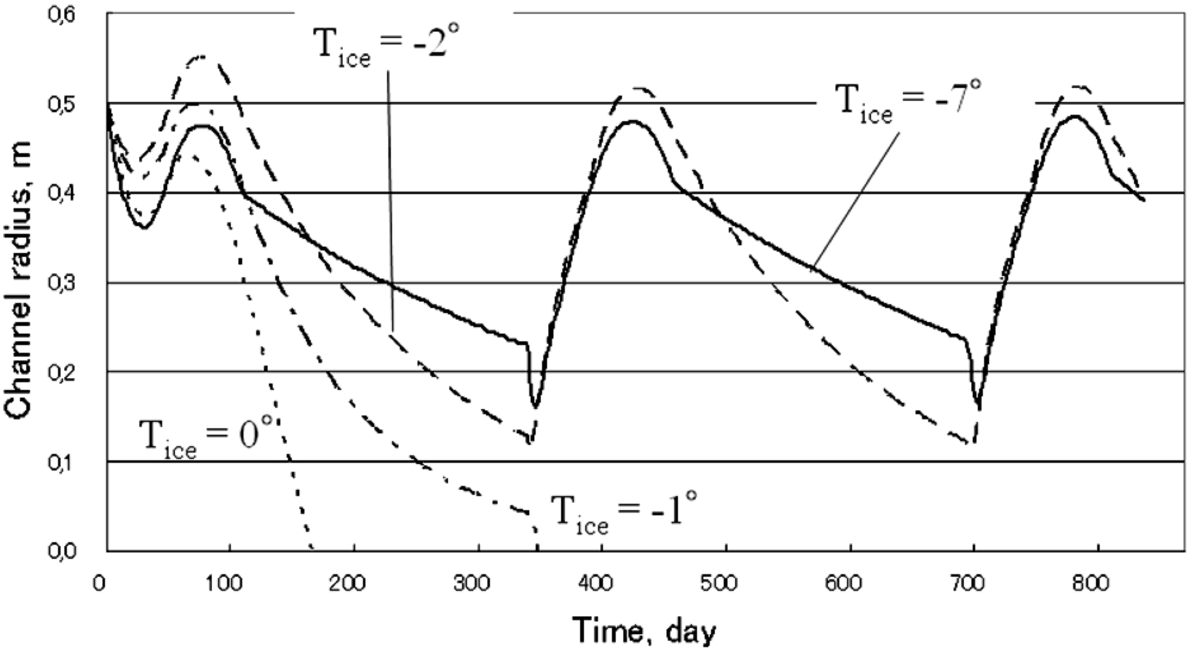

Fig. 4. Development of channels as a result of long-termed simulations. Maximum water discharge 1 m^3/s, slope 0.5°, length 2000 m, depth in ice 100 m

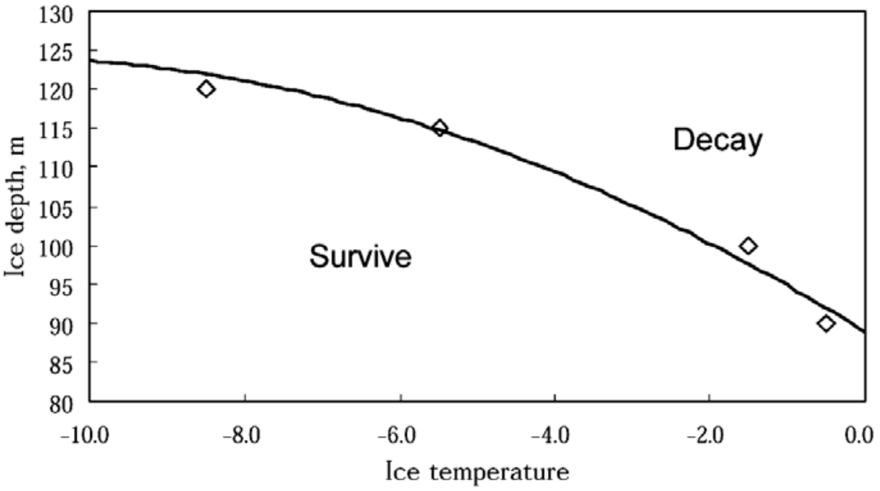

Fig. 5. Criteria of a water channel survival

Reference

Isenko, E.V. (2000) Modeling of channels in cold glaciers. *Data of glaciological studies*, 89, 194-199 (in Russian).

Isenko, E.V., Mavlyudov, B.R. (2001) Rhythmical processes in channels of cold and temperate glaciers. *Data of glaciological studies*, 90, 134-137 (in Russian).

Isenko E.V. (2005) *Development and evolution of water drainage channels in temperate and polar glaciers*. Ph.D. Dissertation, 47 p. Sapporo.

Isenko E.V., Naruse R., Mavlyudov B.R. (2005) Water temperature in englacial and supraglacial channels: change along the flow and contribution to ice melting on the channel wall. *Cold Regions Science and Technology*, 42(1), 53-62.

Röthlisberger, H. (1972) Water pressure in intra- and subglacial channels. *J. Glaciol*., 11(62), 177-203.

Isenko E.V., Mavlyudov B.R., Naruse R. (2005) Survival of developed intraglacial water channels in cold and temperate glaciers. *Glacier Caves and Glacial Karst in High Mountains and Polar Regions*. Ed. B.R. Mavlyudov, 49-53. Institute of geography of the Russian Academy of Sciences, Moscow.