IMPACT OF ARCTIC LAND FAST-ICE GROWTH ON SUBSEA GROUND FREEZING

P.V. Bogorodskii[1], A.V. Pnyushkov[1,2]

[1]Arctic and Antarctic Research Institute, St.Petersburg, Russia
[2]International Arctic Research Centre, University of Alaska Fairbanks, USA

ABSTRACT
A conceptual thermodynamic model of seasonal freezing of water column and underlying layer of bottom sediments, which is based on the solution of heat- and mass transfer equations in saline porous media, was elaborated. This model uses two distinct methods, simulating phase transitions in water and ground layers. Using realistic atmospheric forcing observed at Tiksi Polar Station during the cold season (October-May) 2009-10, land fast-ice and sub-water ground freezing was simulated in the Buor-Khaya Bay (coastal region of the Laptev Sea).

Model simulations showed that the distinguished feature of ice formation at shallow depths (<3m) is a stabilization of ice thickness caused by sub-ice layer salinization. Salinity increase in these zones exceeds an order of magnitude in comparison with the initial salinities (i.e. before freezing) and reaches ~800 psu.

Convective mixing, induced by fast-ice growth, formed uniform sub-ice water layer that remains at the freezing point temperatures. As a consequence of contact of the ground with cold and saline waters, ice formation starts in the bottom sediment layer. In spite of multiple simplifications the model showed relatively good agreement with experimental data obtained by bottom drilling at the Laptev Sea shelf.

INTRODUCTION
Despite several studies of Arctic sub-sea permafrost (e.g., Khimenkov and Brushkov 2003, Osterkamp et al. 1989, Zhigarev 1997), the problem of seasonal freezing of sub-water ground is far from its solution. It is believed that this process starts after complete freezing of the water layer. Thus, possibility of the sub-sea permafrost formation at depths, which exceeds the thickness of fast ice, is often ignored, despite a number of the opposite facts. In this paper we describe a conceptual, one-dimensional, thermodynamic model of sub-water permafrost formation. This model uses two distinct methods, simulating phase transitions in water and sediment layers: frontal (classic) method was implemented for the fast-ice growth, and phase transition in temperature range was used in the ground layer. Consideration of the heat transfer within the adjacent layers as a single process distinguishes this model from its analogues for separate media.

MODEL DESCRIPTION
Freezing of sea water, which contacts with semi-infinite layers of air and water-saturated unfrozen soil, is considered (Figure 1a). Ice formation in the water layer is simulated as the classical (frontal) Stefan problem with prescribed snow accumulation at the upper surface of growing sea ice (Bogorodskii et al. 2010). The freezing of porous water in the ground layer is

described by Stefan problem for the extended two-phase (mushy) area. It is assumed that before ice formation the temperature of water layer becomes close to the freezing point.
Higher rate of heat transfer in comparison with speed of salt diffusion leads to a three-layer pattern of the freezing soil: the upper thawed, mushy, and lower thawed zones (Vasiliev et al. 1997; Figure 1b). In both thawed zones there is no solid phase (ice); in the mushy zone both solid and liquid phases exist in the thermodynamically equilibrium state as a mixture of ice and unfrozen liquid. It is also assumed that the soil skeleton and pore liquid are incompressible and motionless; impurity molecules in the crystalline structure of ice are absent, and all dissolved salt is rejected into unfrozen water during the ice growth. Changes in chemical composition of the liquid phase at phase transition are neglected. The same thermophysical properties of congelation and porous ice (i.e., the coefficients of thermal conductivity and latent heat) were used for simulations, and the heat fluxes within all layers of imitated system are taken as vertically uniform (Nazintsev and Panov 2000, Makshtas 1984, Bogorodskii and Pnyushkov 2007).

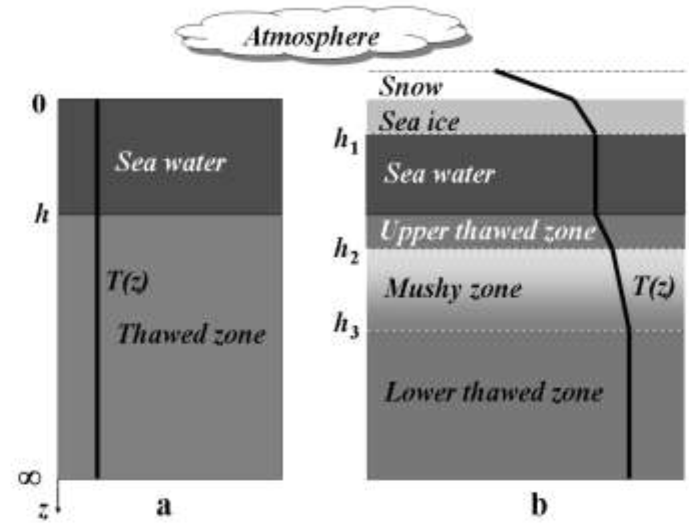

Figure 1. Schematic of temperature distribution $T(z)$ (black line) in the simulated system before (a) and after (b) beginning of freezing, where h_1, h_2, and h_3 are the positions of interfaces between ice-water, thawed-mushy, and mushy-thawed zones, correspondingly; h is the bottom depth.

We implemented this model to simulate sub-sea permafrost evolution in the shallow-water (h~5m) Tiksi Bay (Buor-Khaya Bay, the Laptev Sea shelf) using initial water salinity of 10 psu. Meteorological observations collected at the Polar station Tiksi during the winter of 2009–10 were used to prescribe atmospheric forcing in the thermodynamic model over 240-day period (October 1 - June 1). In addition, we implemented constant geothermal flux (0.06 Wm^{-2}) at the lower boundary of the system.

RESULTS AND DISCUSSION

Simulated fast-ice thicknesses agree well with those observed in the Tiksi Bay during the winter 2009-10 (Figure 2). The model also shows reasonable agreement for the time of transition between ice age stages, i.e. from the initial forms of ice to nilas and annual thick ice. Simulations demonstrate close rates of fast ice growth for all basin depths during the first 70 days of freezing. After 70 days the model shows substantial increase of under-ice water salinity, accompanied by remarkable decrease of ice growth rate. For instance, for 1m basin depth and implemented atmospheric forcing the model showed that the salinity of under-ice water layer exceeds 800 psu (Figure 3). This high salinity corresponds to the freezing temperature of about –40°C. Continuous salinization of the under-ice layer due to brine rejection theoretically excludes its complete freezing even at very small basin depths. An impact of salinization on ice growth decreases with increase of basin depth and becomes negligible at bottom depths greater than 3 m (Figures 2, 3). Assuming large shallow areas of the Laptev Sea shelf we speculate that the volume of extra saline waters can be significant.

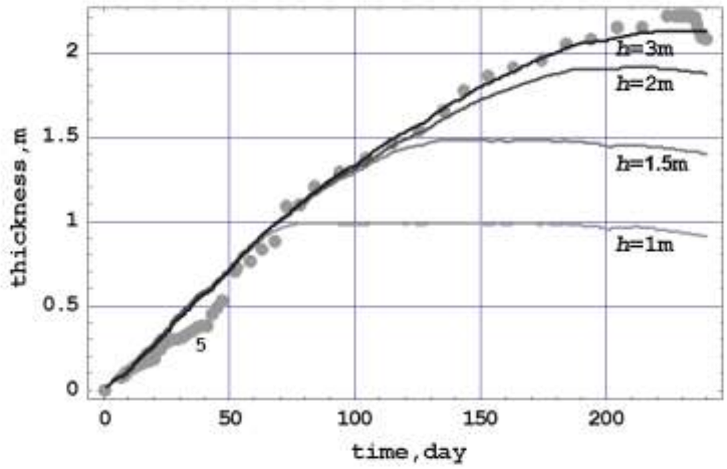

Figure 2. Ice thickness (h_1) simulated for 1, 1.5, 2 and 3 m basin depth (h). Gray circles denote observed ice thickness measured in the winter season 2009-10 in the Tiksi Bay at 3-m depth.

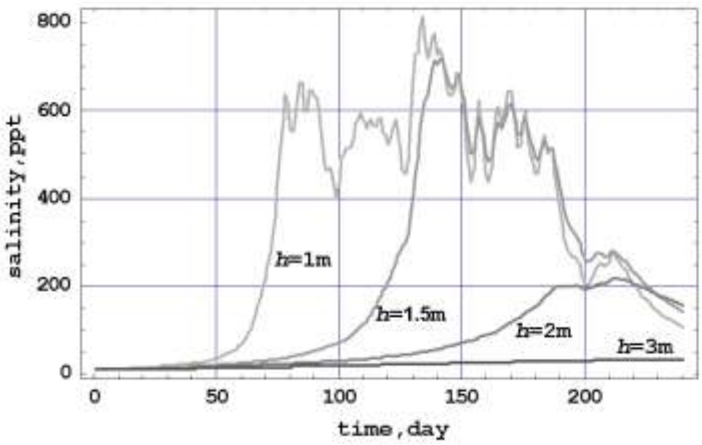

Figure 3. Simulated under-ice water salinity for 1, 1.5, 2, and 3 m basin depth (h).

When the upper ice surface temperature exceeds the temperature at the lower interface the heat flux through the ice changes its direction. According to the Stefan condition this leads to ice melting, even at negative air temperatures. This effect is more evident in shallow-water areas, where the simulated temperature differences between the upper and lower ice interfaces are relatively small (Figure 4). Therefore, in the Tiksi Bay the fast-ice can simultaneously growth in deep-water areas and melt in the shallow parts.

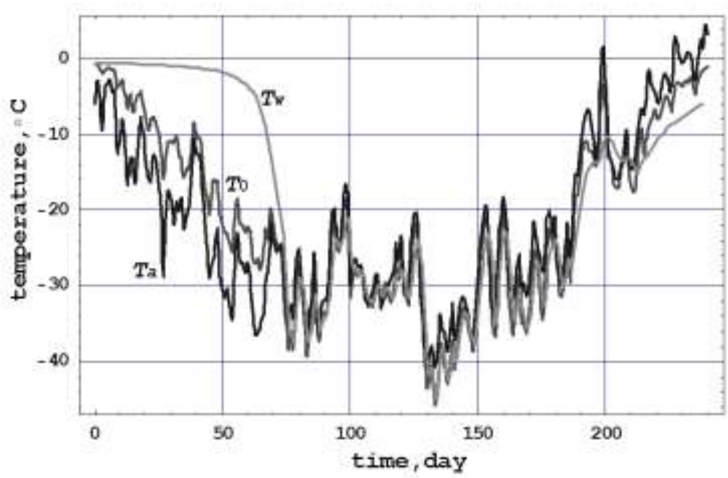

Figure 4. Observed air temperature (T_a) and simulated temperatures of snow-ice (T_0) and ice-water (T_w) interfaces for 1 m basin depth.

The rates of fast- and pore-ice formation have similar features, which are governed, in general, by total water depth (Figure 5). Extremely low temperatures of the sub-ice water layer leads to accelerated freezing of the ground layer, and are accompanied by growth of mushy zone. The model shows low sensitivity of sub-water permafrost thickness to the initial water salinity. For example, for 1.5-m basin depth an increase of salinity from 5 to 25 psu leads to increase of the mushy zone at 0.1 m only (from 3.4 to 3.5 m). Maximal thicknesses of the upper thawed zone, which is developed by permanent contact with brine and supported by slow salt diffusion, was found as 18 and 4 millimeters at 1 and 3-m basin depths, respectively.

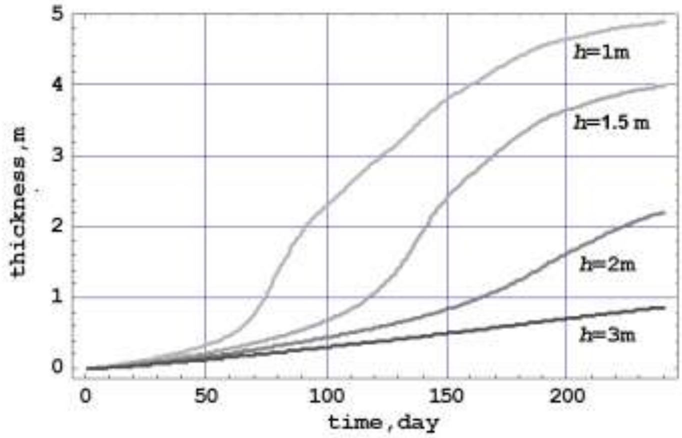

Figure 5. Simulated thickness of mushy zone for 1, 1.5, 2, and 3 m basin depth (h).

In spite of relatively good agreement between the simulated and observed fast-ice thicknesses the model has several potential weaknesses. For instance, the model does not include lateral mixing and advection because of one-dimensional implementation. We note however, that for local depth depressions the magnitude of advective tidal salt fluxes cannot have strong impact on the rate of underice layer cooling and thus, the growth rates of sub-sea permafrost on seasonal time scales. In addition, the implied condition of thermodynamic equilibrium restricts supercooling of the liquid phase within mushy zone. The existence of this effect for the sub-sea permafrost is confirmed by several laboratory experiments (e.g., Zhigarev 1997).

CONCLUSIONS

The elaborated conceptual model is aimed to study natural processes of sub-water permafrost formation and applicable for a wide range of meteorological conditions. In particular, this model successfully described the freezing within contacted layers of sea water and ground in near-shore areas of the Laptev Sea shelf. Relatively good quality of the model is confirmed by sufficiently good agreement with observations collected in the Russian-German collaborative permafrost studies (Junker et al. 2008, Rachold et al. 2007). The model reproduced formation of the under-ice brine layer, which theoretically cannot be frozen even at very low air temperatures. Salinization of the under-ice layer causes ice melting at negative air temperatures, so that the fast-ice can simultaneously growth in deep-water areas and melt in the shallow parts. The freezing of sea water and ground layers begins simultaneously, however, has significantly different rates. The dense super-cooled waters have strong influence on phase transition processes, and therefore on mechanical properties of frozen ground.

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