Thermal Regime of Frozen Soils with Snow Covers at Combined Radiant and Convective Effects

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Abstract. The paper examines the variability of the temperature profile (including the generation of its inversion by combined radiant and convective action) for the exposed snow cover, which determines the thermal regime of the underlying medium (dense firn or frozen soils and ground of low- and high-lands) in view of heating by a geothermal thermal influx. Experimental and theoretical researches allowed studying the effects daily radiating-conductive heating inside a snow layer (covered the underlying glaciological mediums) at conditions of the external impact by atmosphere convection (together with longwave thermoradiation) and solar shortwave penetrating thermoradiation. The possibility of the formation of heat conductive fluxes redirected to exposed superficial during subsurface radiant overheating - was shown theoretically in order to prevent thawing of the underlying media. For the first time inversion temperature profiles were registered inside snow thickness on the glacier surface near Elbrus at the height \(\sim 4000\) m. The authors interpreted this effect from the standpoint of scattering media optics. Snow cover was modeled as a semitransparent medium with volumetric albedo, scattering and absorption indices (coefficients), caused by the calculated parameter of internal radiant heat source function, corrected by the experimentally measured temperature profile of the investigated snow layer. It is shown that during the morning hours at intensive insolation and atmospheric negative temperatures, subsurface overheating inside the glacier is produced. This phenomena was observed experimentally on depth up to 5-40 sm using of thermodes of long measure probe. The obtained results are in the consent with theoretical estimations of authors and foreign researchers.

1. Introduction
Influence of snow cover on soil freezing is subject numerous and multi-year research in the low-land [1-7]. A feature of current researches is the study of permafrost in the high-lands due to intensive industrial development in Russian Siberia and Chinese Tibet [8-12].

Thus, the problem of stabilization of the thermal regime of frozen ground becomes extremely urgent. In the high-lands under conditions of intense solar exposure and low atmospheric temperatures, snow cover can be interpreted as a heat insulator, as well as a cooler depending on the
season. The spectral composition of solar radiation and the structure of the exposed snow and ice media will ensure the generation of its unusual temperature fields and significantly affect the underlying environment [5-6, 13-15].

In glaciology, at studying daily and seasonal oscillation of temperature in the glacier thickness, the radiative component of the total heat flux is usually taken into account only in heat balance on the exposed surface. The effect of the radiative component of the external heat load on the internal heating of the snow and ice is still insufficiently investigated [1-7, 13, 16, 17].

Interpretation of radiative heat transfer is not corrected enough both in classical [5-7, 16] and modern studies [17] especially in comparison with the developed methodology of the scattering theory in other fields aerodynamics, nuclear physics based on research of semitransparent thermal barrier coatings [18-21]. Only in a few books, papers the effect of subsurface radiant overheating and melting of snow was experimentally observed [6, 13, 22]. There are theoretical evaluations of distributions of absorbed radiant energy using only Bouguer law [16, 17] and base on full solution [14, 15, 23] of radiative heat transfer equations. Conducted research allowed us to propose a number of technical solutions aimed at controlling the melting of glaciers [24] and freezing of soils [25].

Theoretical studies also confirm that overheating and melting inside the snow thickness internal can generate even at low ambient temperatures, but during intense external insolation [14, 15]. It was shown that the albedo and the function of absorbed energy (causing subsurface heating) are determined by the combined effect of absorption and scattering in a semitransparent glacial cover under the action of the shortwave penetrating component of external thermal radiate flux.

It should be noted that there are many works devoted to the measurement spectral fluxes of solar and atmospheric radiation and phenomenological reflection and transmission coefficients for different glaciers. But the connection between the structure of snow and ice, its optical properties (scattering and absorption) and the absorbed radiation is absent in most works [5-7, 16, 17, 26-30].

It was shown that the albedo and the function of absorbed energy (causing subsurface heating) are determined by the combined effect of absorption and scattering inside a semitransparent glacial cover under the action of the shortwave penetrating component of external thermal radiate flux. In this case, the spectral composition of the incident radiation is significant, because it defines the absorption inside the of snow-ice cover or on its surface. Ice is a low absorbing medium with an absorption index of $\kappa \sim 0.01 \pm 1 \text{ m}^{-1}$ [5, 6, 14, 26-28, 30] for solar radiation in the wavelength range of $\lambda \sim 0.4$-1 $\mu$m. For infrared thermal emission spectrum of the atmosphere snow and ice can be considered almost as completely black body with radiant absorption on the exposed surface.

But for a part of the solar flux $q_s$ in the near UV $\sim (\lambda \sim 0.3$-0.4 $\mu$m) and in the near IR regions $(\lambda > 1 \mu$m) of the spectrum, snow and ice are also opaque and strongly absorbing media with a fraction of absorbed energy $q_s^{UR}, q_s^{IR} \sim (0.1-0.2) \cdot q_s$ [14, 16, 29].

This must be considered at solving a nonlinear boundary problem of radiant and convective heat transfer.

2. Optical models of snow cover

The optical characteristics of natural ices without significant structural defects are characterized by an extinction index (attenuation coefficient) $b$ in the internal $0.1 \pm 5 \text{ m}^{-1}$ (with albedo $A \sim 10$-40%), and for snow $b \sim 1 \pm 100 \text{ m}^{-1}$ ($A$ changes up to 99%) in the shortwave range [6, 14, 16, 26-28, 30]. For weakly scattering ice, this parameter actually corresponds to the experimentally measured absorption index $\kappa$.

But at the study of the optical properties of semitransparent snow and “white” ice, the extinction index $b$ is the integration value including absorption $\kappa$ and a scattering $\sigma$ indexes.

The question of the correction of the terms used in glaciology in accordance with the general physical definitions and characteristics (in particular for the optics of scattering media) still remains topical.
The proposed optical models are based on these optical data and have the following classification in the symbolical form for snow medium s (σ / κ - A). The input value of the volumetric scattering σ and absorption κ indexes has the traditional interpretation in the optics – as the fraction of the scattered (absorbed) energy per unit length of the inhomogeneous media or material.

Though these parameters define radiation transfer in model one-dimensional semitransparent medium they have physical sense in microscopic representation. These parameters are proportional to integral diffraction cross-sections of scattering Σs and absorption Σa (m²) for polydisperse fractions of scattering and absorbing model spherical ice particles with effective diameter D. Then the optical parameters are estimated depending on the wavelength of the solar radiation, the complex refractive index and the snow structure, due to the size of the crystals (or their size distribution function). For monodisperse media the absorption and scattering indexes are

\[ \kappa \approx N \cdot k_s \cdot \pi \cdot D^2 / 4, \quad \sigma \approx N \cdot k_a \cdot \pi \cdot D^2 / 4. \]

In these formulas absorption \( k_a \) and scattering \( k_s \) factors are functions of known the G.Mie coefficients; \( N \) is concentration of scatterers or the number of pores for ceramic materials and coatings [14, 28].

In the microscopic representation, the scattering index is an integral value calculated using the factors (cross sections) of scattering (in the framework of G. Mie theory [14, 28]), taking into account the distribution function of the concentration of polydisperse particles (with effective sizes comparable to radiation wavelength).

Optimization of optical snow models should be preceded by the selection of an acceptable thermal regime. The optical model s (100 / 2–79) of well-scattering natural freshly snow can quickly turn into another model modification, for example, describing the firn s (25 / 1–75) or urban snow s (100 / 4–69) polluted with soot. Comparison of these models shows that the increasing of the absorption index \( \kappa = 1...4 \text{ m}^{-1} \) more significantly can decrease the albedo value \( A = 79...75...69\% \), in contrast with same changing value of the scattering index but its decreasing \( \sigma = 100...25 \text{ m}^{-1} \).

In the presented optical modeling, the authors used engineering formulas for estimating of the radiant and temperature fields for industrial materials and natural environments in accordance with the methodology developed by the authors [14, 15, 18, 21].

3. Radiation-conductive mechanism of volumetric heating for snow layer
According to the formulated optical models, we analyze the successive stages of heating (up to the beginning of melting) of a plane-parallel layer of freshly falling snow s (100 / 2–79), firn s (10 / 1–64) with different densities and thermal conductivities.

In general, conductive and radiant heat transfer with a known spectral function of the absorbed shortwave solar energy (as well as the energy losses for phase transitions on surface or inside the volume of the exposed snow cover) is the typical nonlinear boundary value problem - as an equation relative to the temperature profile \( T(z,t) \) for the one-dimensional case. To this equation it is necessary to add the condition of heat transfer on the surface \( z = 0 \) as a result of the effect of the atmosphere convection and the longwave length radiant flux and part of the solar flux (spectrum in UV- and IR-radiation) absorbed only by the surface.

To analyze the influence of optical and thermal physical parameters on the temperature field \( T(z,t) \) of snow cover at action of convective and radiant heat loads, we considered only for the thermally insulated rear flat boundary for a thick layer ~ 1 m. Then for a typical thermal conductive heating (during the time at several hours) heat sink at the rear border is insignificant. Insolation (penetrating thermal radiation) will be significant also only at a small depth ~ 30 sm for selected optical models.

At simulation \( T(z,t) \) the initial temperature of the snow is taken for moderate glaciers with middle temperatures \( T_0(z,t) = -8^\circ\text{C} \). In experimental measurements of the temperature for a real glacier - the initial profile was recorded as steady state to the morning hours.

The dependence of thermal and optical characteristics on temperature is also neglected. Coefficient of convective heat transfer \( \alpha_T = 5 \text{ W} / (\text{m}^2\cdot\text{K}) \) was used as characteristic of arid and high mountain zones [5-6]; the value of the solar radiation flux \( q_0 = 375 \text{ W} / \text{m}^2 \) [5, 6, 13, 16, 29].
4. Results of model calculations of temperature fields inside semitransparent snow covers
As soon as there are conditions of a negative heat balance at the frontal boundary of the semitransparent snow cover, heat conductive flux begins change its direction. Heat sink the is produced from the depth of snow cover (the temperature maximum point) to its surface. So the effect of temperature inversion occurred in the subsurface region of the snow layer (Fig. 1). This effect is caused by the cooling of the surface glacier due to longwave radiation and convective heat fluxes with continued absorption of penetrating solar radiation.

\[ a \]

\[ b \]

\textbf{Figure 1.} Simulated temperature distributions \( T(z,t) \) inside homogeneous layer of snow with optical models: \( a \) - \( s \) (100/2–79) – fresh snow (heat conductivity \( K_T=0.5 \) W/m·K, density \( \rho=500 \) kg/m\(^3\)); \( b \) - \( s \) (10/1–64) - firn (\( K_T=0.7 \) W/m·K, \( \rho=700 \) kg/m\(^3\)).

Upper part of Elbrus glacier: convective (\( \alpha_T=5 \) W/m\(^2\)·K), atmosphere (blackbody with temperature \( T_A \)) and solar (\( q_0=375 \) W/m\(^2\)) thermal radiation fluxes.

Heating time \( t = 6 \) hour, \( T_0(z) = -8 \) °C, \( T_A = 16 \) °C (curve -T1); -8 °C (T2); -4 °C (T3).

Thus, with energy losses on the exposed surface comparable to a penetrating radiant flux, a maximum of the temperature profile begins to form in the subsurface region, for example, at a depth of \( \sim 5–40 \) cm depending on the temperature of the atmosphere for model \( s \) (100 / 2—79) (Fig. 1, a) and at more large depths for weakly scattering covers of other model for firn \( s \) (10/1–64) (Fig. 1, b). With increasing air temperature, the temperature maximum in the snow thickness was moving to the exposed surface.

Surface heat absorption begins to prevail over the volumetric absorption of radiant energy.

5. Experimental measurements of the subsurface temperature maximum snow cover of the mountain glacier
To record the temperature horizon (within deep layers of snow cover) a temperature-sensitive sensor transducer was used, made in the form of measure probe 1 m long and 4 mm in diameter (representing the chromel-alumel thermocouple) according to Russian standard GOST R 8.585 (Fig. 2, 3).

On the figure 2 the calculated and experimentally measured temperature profiles for the freshly snow thickness of the upper part of the mountain glacier are shown. It is the southeastern slope near Elbrus at height \( \sim 4000 \) m (April) with the test site, transverse to the sun’s beams. The registration of the temperature profile occurred in the morning hours 8.00-8.30 with the beginning of solar radiation with cloudless sky.
Figure 2. Simulated (curve T1) and experimental (T2, T3) temperature distributions $T(z,t)$ at: initial (8.00 - T2) and final (8.30 - T1, T3) times. See Fig.1 - external condition and Fig. 3 - glacier structure with fresh snow thickness ~ 1 m with optical model s(100/2-79).

The main result of the measurements is the observation of increasing temperature in the subsurface horizons of the snow cover (relatively to the almost steady state surface and atmosphere temperatures $-8 \, ^{\circ}C$ at the morning hours). In half past hour the internal maximum $T_{max} = -1.3 \, ^{\circ}C$ was achieved with coordinate $z_m = 5-6 \, sm$. At great depths in the snow cover thickness the temperature gradually transformed into a temperature profile corresponding to the night temperature.

6. Conclusions
In this work, influence of thermal regime of semitransparent snow cover on soil freezing was presented using the theoretical and the experimental technic. A feature of current researches is the study of variability permafrost in the highlands, due to intensive industrial development in Russian Siberia and Chinese Tibet.

It was investigated the effects daily radiating-conductive heating of a snow covers on the underlying glaciological mediums at conditions of the external impact of atmosphere convective and solar thermoradiation heat load. For the first time inversion temperature profiles were registered inside...
snow thickness at intensive penetrating solar radiation in the high-lands and were explained theoretically from the position of the scattering media optics.

Previously, this effect was most reliably recorded in Antarctica [13].

Thus, the state of the snow surface (including the application different solid (perforated) semitransparent film coating [24, 25, 31] and opaque gravel layers) will determine the temperature changing of subsurface heating and allow you to control the stabilization of the thermal regime of underlying soils and grounds.

The proposed optical models of snow cover allowed us to associate the natural structural states of snow with their optical characteristics. Some of the optical parameters (albedo, absorption index) have traditionally been used in glaciology. But they were supplemented with new characteristics that determine the volume reflection of a snow layers - the scattering σ and excitation b indexes.

This paper will be useful for scientists and engineers to perform forecast estimates of thermal regimes of frozen soils controlled by model structured snow cover including the use of additional surface heat insulation coatings.

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