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SNOW COVER AND GLACIERS

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EFFECTIVE THERMAL CONDUCTIVITY OF SNOW AND ITS VARIATIONS

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Various empirical relationships of thermal conductivity vs. density and temperature are compared and analyzed in terms of applicability to estimation of the effective thermal conductivity of snow. The contributions of water vapor diffusion and air convection to the effective thermal conductivity of a snowpack of different temperatures and densities are estimated by mathematical modeling. Experimental estimates of the effective thermal conductivity of snow are reported for mid-latitude European Russia. The experimental results are compared with those obtained by other authors.

Water vapor diffusion, effective thermal conductivity, snow, density, temperature, heat and mass transfer

INTRODUCTION

The snow cover is an important agent in heat exchange between ground surface and near-surface air [*Pavlov, 2008*]. The effect of snow parameters on ground freezing was discussed in our previous publications [*Osokin et al., 1999, 2000, 2006*]. The heat insulation properties of snow depend on its thermal conductivity which, in turn, has multiple controls: density and temperature, as well as structure of snow that affects heat and mass transfer [*Osokin et al., 2013a,b*].

Heat in solids is transferred between fixed particles mainly by molecular exchange and results from their activity. Faster motions (oscillations) of particles in a solid increase its temperature. When more mobile particles, with greater energy, collide with less mobile ones, the molecular heat transfer is from a higher energy level to the lower level, by conductive mechanisms. The share of conductive heat transfer is lower in less dense materials which have a smaller surface area of molecular contacts. Heat transfer in liquids and gases is mainly by convection, at the account of particle motion.

Heat transfer through snow, which is a porous solid, proceeds by both conduction (between ice crystals) and convection (diffusion of water vapor and interstitial air flows) mechanisms. Diffusion is driven by gradients of vapor pressure depending on temperature gradients in the snowpack, and these control conductive heat transport between fixed snow particles. As a result, heat flux in a snowpack depends on its temperature gradient called effective thermal conductivity of snow [*Pavlov, 2008*] consisting of two components that correspond to conductive and convective (water vapor diffusion) heat transfer.

The two components are hard to separate during heat flux determination, and thermal conductivity including both ways of heat transport is used in the common practice instead of the effective value.

The estimates of snow thermal conductivity (λ_s) are commonly presented as its empirical relationships, mostly with snow density. Reviews of main published thermal conductivity vs. density empirical relationships can be found in [*Sturm et al., 1997; Osokin et al., 2000*]. Some publications reported also equations for temperature dependence of thermal conductivity [*Pitman and Zuckerman, 1967; Pavlov, 1979; Fukusako, 1990; Sturm et al., 1997*].

The effect of snow structure and texture (particle sizes) on thermal conductivity has been considered either significant [*Sturm et al., 1997*] or negligible [*Pavlov, 2008*]. This effect may be weak because the surface contacts of snow particles become fewer as the particles grow larger. On the other hand, each growing particle increases its specific surface area, and the total specific area of particle contacts as a control of λ_s does not change much.

Snow thermal conductivity λ_s depends on heat transport mechanisms: conduction by ice skeleton (λ_c); water vapor diffusion; and air convection in the pore space. Note that the amount of heat transported by these mechanisms has multiple controls. For instance, air convection in a snowpack is governed by temperature gradients between snow layers which also influence the concentration and diffusion rate of water vapor. The rate of heat transport depends more or less strongly on snow density, the govern parameter in various existing empirical relationships for snow thermal conductivity.

SNOW THERMAL CONDUCTIVITY

There exist several tens of empirical relationships ‘thermal conductivity λ_s vs. density’ for snow of different types and temperatures. Average values were obtained on the basis of twenty published relationships [*Osokin et al., 1999*]: average λ_s (in W/(m·K)). were calculated for each density value, at every 10 kg/m^3. The resulting curve of average λ_{sa} was approximated as

$$\lambda_{sa} = 9.165 \cdot 10^{-2} - 3.814 \cdot 10^{-4} \rho_s + 2.905 \cdot 10^{-6} \rho_s^2. \quad (1)$$

In order to cover the entire range of thermal conductivities, relationships were obtained for the upper and lower envelopes of their variance, respectively:

$$\lambda_{su} = 1.36 \cdot 10^{-2} + 1.1 \cdot 10^{-3} \rho_s + 10^{-6} \rho_s^2; \quad (2)$$

$$\lambda_{sl} = 2.96 \cdot 10^{-2} - 3 \cdot 10^{-4} \rho_s + 2 \cdot 10^{-6} \rho_s^2, \quad (3)$$

where ρ_s is the snow density, kg/m^3.

Equations (2) and (3) demonstrate the possible variation range for the analyzed relationships. The available empirical relationships of ‘thermal conductivity λ_s vs. temperature’ are much fewer. One suggested by *Pavlov* [*1979*] uses the temperature coefficient (K_P) to estimate the effect of water vapor diffusion on the thermal conductivity of snow with a density of 120 to 350 kg/m^3. K_P is found as

$$K_P = 1 + 1.18 \exp(0.15 t_s), \quad (4)$$

where t_s is the snow temperature, °C.

Thermal conductivity (λ_{sP}) is [*Pavlov, 1979*]

$$\lambda_{sP} = \lambda_{cP} K_P, \quad (5)$$

where λ_{cP} is the conductive thermal conductivity of snow given by [*Pavlov, 1979*]

$$\lambda_{cP} = 0.035 + 0.353 \cdot 10^{-3} \rho_s - 0.206 \cdot 10^{-6} \rho_s^2 + 2.62 \cdot 10^{-9} \rho_s^3. \quad (6)$$

The latter relationship (6) corresponds to the conductive component as it was obtained from measurements at snow temperatures below −25 °C [*Pavlov, 1979*].

The thermal conductivity of snow can be estimated using the simplified relationship (λ_{sP1}, W/(m·K)) [*Pavlov, 2008*]:

$$\lambda_{sP1} = 10^{-3} \rho_s. \quad (7)$$

This equation is valid within the snow temperature range from −10 to −20 °C, but additional 0.04 W/(m·K) should be added to or subtracted from λ_s in the case of warmer or colder snow, respectively. This correction allows for heat transfer by diffusion of water vapor.

Equation (7) is close to the relationship suggested by Proskuryakov which is the best suitable for analysis of active layer freezing [*Balobaev, 1991*]:

$$\lambda_s = 0.021 + 1.01 \cdot 10^{-3} \rho_s. \quad (8)$$

The λ_{dh} equation by *Sturm et al.* [*1997*] at t_s = 0 to −40 °C

$$\lambda_{dh} = \lambda_{fs} + 51.8/((t_s - 27.8)^2 + 211.2), \quad (9)$$

where λ_{fs} = 0.06 W/(m·K) is the thermal conductivity without regard to water vapor diffusion.

The thermal conductivity of granular snow λ_{gs} is found as [*Sturm et al., 1997*]

$$\lambda_{gs} = 0.138 - 1.01 \rho_s + 3.233 \rho_s^2$$

$$\text{at } 0.156 < \rho_s < 0.6 \text{ g/cm}^3, \quad (10)$$

$$\lambda_{gs} = 0.023 + 0.234 \rho_s \text{ at } \rho_s < 0.156 \text{ g/cm}^3.$$

Currently the equation by *Sturm et al.* [*1997*] (10) is often applied to glaciers.

Regional relationships for thermal conductivity were also obtained [*Pavlov, 1984*] from the equation of De Vries for a two-phase material:

$$\lambda_s = \frac{\lambda_a \nu_p + \lambda_i (1 - \nu_p) F_s}{\nu_p + (1 - \nu_p) F_s}, \quad (11)$$

where λ_a and λ_i are the thermal conductivities of air and ice, respectively, W/(m·K); $\nu_p = 1 - \rho_s/\rho_i$ is the porosity; ρ_i is the ice density, kg/m^3; F_s is a parameter that approximates experimental data from Yakutsk (at F_s = 0.15) and Igarka (F_s = 0.25).

In our earlier experimental studies in the Moscow region [*Chernov, 2013; Osokin et al., 2013b*], the thermal conductivity of different snow types varying in density was estimated from heat flux data and temperature gradients measured in undisturbed snow placed in a cooling chamber. The measurements were taken in a temperature range of −2 to −22 °C, and the thermal conductivity estimates were obtained for granular, drift (blown), and new snow, and for depth hoar (Fig. 1). Linear approximation of the empirical values led to the following equations for the thermal conductivity of granular snow λ_{gs1} (density from 100 to 400 kg/m^3), blown snow λ_{bs} (190 to 310 kg/m^3), new snow λ_{ns1} (80 to 170 kg/m^3) and depth hoar λ_{dh1} (over the measured density range from 185 to 450 kg/m^3):

$$\lambda_{gs1} = 0.9455 \cdot 10^{-3} \rho_s - 0.0034, \; R^2 = 0.5103; \quad (12)$$

$$\lambda_{ns1} = 0.5027 \cdot 10^{-3} \rho_s + 0.0024, \; R^2 = 0.4098; \quad (13)$$

$$\lambda_{dh1} = 0.6360 \cdot 10^{-3} \rho_s - 0.0231, \; R^2 = 0.7121. \quad (14)$$

For depth hoar, with particle sizes from 0.8 to 1.5 mm and densities from 185 to 310 kg/m^3:

$$\lambda_{dhf} = 0.4304 \cdot 10^{-3} \rho_s + 0.0225, \; R^2 = 0.3177.$$

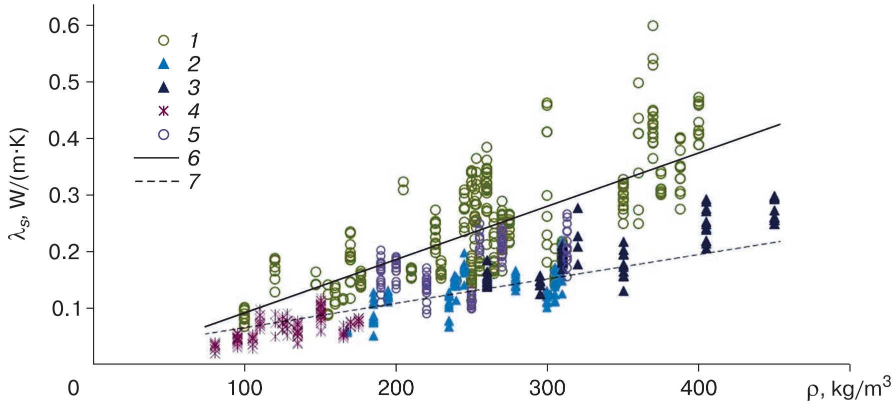

Fig. 1. Thermal conductivity (λ_s) vs. density for snow from Moscow region:

1 – fine, medium, and coarse snow; *2*, *3* – depth hoar with 0.8–1.5 mm (*2*) and 1–3 mm (*3*) grain sizes; *4* – new snow; *5* – blown snow; *6*, *7* – trends for granular snow and 0.8–1.5 mm depth hoar, respectively.

For depth hoar, with crystal sizes 1–3 mm and densities 260–450 kg/m^3:

$$\lambda_{dhc} = 0.6232 \cdot 10^{-3}\rho_s - 0.0115,\ R^2 = 0.6842.$$

The relationship for blown snow, at a density range of 190 to 310 kg/m^3 becomes

$$\lambda_{bs} = 0.535 \cdot 10^{-3}\rho_s + 0.0458,\ R^2 = 0.2452.$$

The parabolic relationship for granular snow $\lambda_{gs2} = 1.6099 \cdot 10^{-6}\rho_s^2 + 0.1039 \cdot 10^{-3}\rho_s + 0.0977$, $R^2 = 0.5236$ only slightly improves the accuracy relative to equation (12) within the main density range.

The general relationship for thermal conductivity of snow, irrespective of its type (trend based on all points in Fig. 1) is given by

$$\lambda_{sum} = 0.8682 \cdot 10^{-3}\rho_s - 0.0278,\ R^2 = 0.56. \quad (15)$$

The thermal conductivity $\lambda_{ns} = 0.06$ W/(m·K) of new dry snow in equation (9) corresponds to the density of new snow 115 kg/m^3, according to equation (13) for λ_{ns1}.

THERMAL CONDUCTIVITY RELATIONSHIPS: COMPARATIVE ANALYSIS

Thermal conductivity estimates based on different relationships with density (regression curves) are compared in Fig. 2. The values λ_{sP} found with equation (5) [*Pavlov, 1979*] at the snow temperature $t_s = -1$ °C approach the maximum λ_{su} calculated from the upper envelope, according to (2). Note that λ_{sa} estimated with (1) approximately coincides with λ_{sP} found by (5) at $t_s = -10$ to -12 °C and is intermediate between the curves for Yakutsk and Igarka (Fig. 3). The λ_s values for Yakutsk are below the minimum λ_{cP} calculated by (6) but are much greater than λ_{sl} based on the lower envelope (equation 3), which correspond to those for snow in Antarctica with temperatures of –30 to –40 °C.

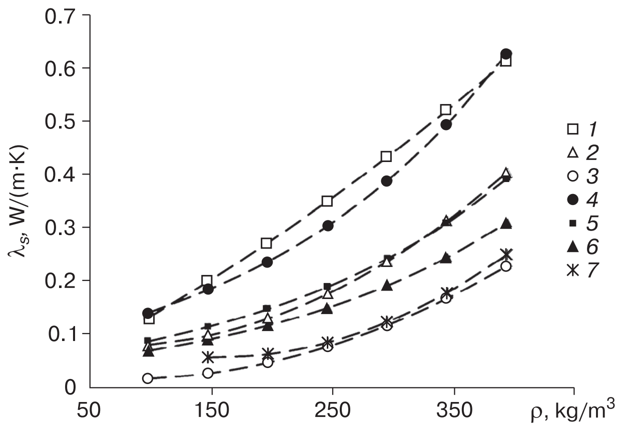

Fig. 2. Thermal conductivity (λ_s) vs. density regression curves for snow:

1 – equation (2); *2* – equation (1); *3* – equation (3); *4* – equation (5) at $t_s = -1$ °C; *5* – equation (5) at $t_s = -10$ °C; *6* – equation (6); *7* – equation (10).

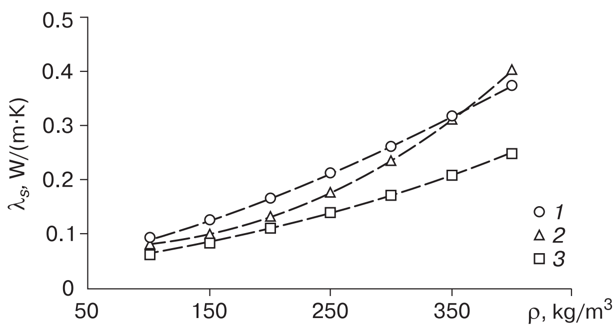

Fig. 3. Thermal conductivity (λ_s) vs. density regression curves for snow:

1 – equation (11) for Igarka; *2* – equation (1); *3* – equation (11) for Yakutsk.

Calculations with equation (10) of *Sturm et al.* [*1997*] give small thermal conductivity values. Namely, they range from 0.07 to 0.13 W/(m·K) for granular snow with a density of 200 to 300 kg/m^3 which is 2–3 times lower than the values found by (1). The thermal conductivity of depth hoar calculated with (9) is 0.08–0.09 W/(m·K) at –10 to –20 °C, or below the values for granular snow found with (10).

The thermal conductivity estimated with equation (10) of *Sturm et al.* [*1997*] approaches the minimum values based on the lower envelope, equation (3) (Fig. 2). The underestimation of thermal conductivity values by the equation of *Sturm et al.* [*1997*] was also noted by *Calonne et al.* [*2011*] who simulated the conductivity of snow using microtomographic images (3D images of snow microstructure) spanning all types of seasonal snow. As a result, the relationship was obtained

$$\lambda_s = 2.4\cdot10^{-2} - 1.23\cdot10^{-4}\rho_s + 2.5\cdot10^{-6}\rho_s^2 \qquad (16)$$

with possible λ_s scatter around the regression curve. The λ_s values calculated from this relationship (Fig. 4) are 0.03 W/(m·K) lower than those calculated with equation (1).

According to [*Sturm et al., 1997*], the thermal conductivity of depth hoar with a density of 215 kg/m^3 at –4 to –0.5 °C is within 0.07–0.11 W/(m·K). Measurements in the Moscow region and calculations by (14) gave 0.10–0.11 W/(m·K) at the same density (Fig. 4). Depth hoar of a higher density (200 to 350 kg/m^3) has 1.5 times higher average thermal conductivity: from 0.06 to 0.09 W/(m·K) [*Sturm and Johnson, 1992*], while calculations based on empirical relationships show thermal conductivity increase from 0.10 to 0.19 W/(m·K). Note that the depth hoar thermal conductivity λ_{dh1} estimated by (14) within the density range 200–400 kg/m^3 is 1.6–1.8 times lower than the λ_{gs1} values of granular snow according to equation (12).

The λ_s values found by equation (8) of Proskuryakov [*Balobaev, 1991*] are 0.023 W/(m·K)

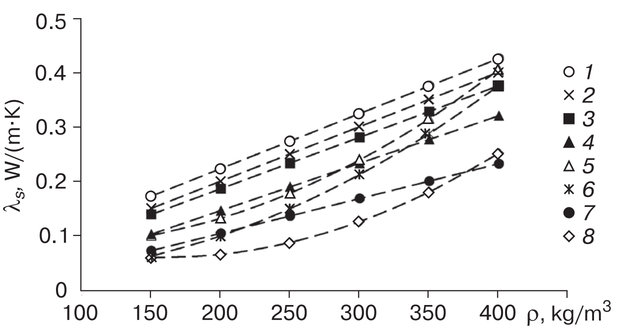

Fig. 4. Thermal conductivity (λ_s) vs. density regression curves for snow:

1 – equation (8); *2* – equation (7); *3* – equation (12); *4* – equation (15); *5* – equation (1); *6* – equation (16); *7* – equation (14); *8* – equation (10).

higher than those calculated with the simplified equation (7) [*Pavlov, 1979*], and 0.04 W/(m·K) greater than the thermal conductivity of granular snow from the Moscow region (equation 12). The thermal conductivity λ_{sa} found by equation (1) is 0.03 W/(m·K) higher than that calculated with (16). Note that calculations with (15) obtained for the conditions of the Moscow region, without regard to the snow microstructure, agree within 3–10 % with equation (1) obtained by averaging twenty known relationships and differ for ~0.01 W/(m·K) within the density range 150–300 kg/m^3. The thermal conductivities of snow in Fig. 1 are beyond the limits of envelopes calculated by equations (2) and (3).

EFFECT OF SNOW MICROSTRUCTURE ON THERMAL CONDUCTIVITY

Thermal conductivity varies as a function of snow microstructure, which is evident in λ changes with density and size of snow particles. The trend of λ_{dh} values for depth hoar with fine crystals (0.8–1.5 mm) and a density of 200–300 kg/m^3 actually continues the trend for new snow with a density of 80–175 kg/m^3, their difference in the trends being within 1–5 %.

Coarser depth hoar (1–3 mm), with its density of 300 kg/m^3, has 16 % greater thermal conductivity than the fine (0.8–1.5 mm) variety. Thermal conductivity of blown snow (λ_{bs}) with a density of 180–310 kg/m^3 is 21–36 % lower than that of granular snow λ_{gs}, while the latter is 71–85 % higher than in 0.8–1.5 mm depth hoar of 200–300 kg/m^3 and 60–57 % higher than in the coarser and denser depth hoar (1–3 mm and 300–450 kg/m^3).

TEMPERATURE DEPENDENCE OF SNOW THERMAL CONDUCTIVITY

As follows from the above analysis, thermal conductivity variations in snow depend on its temperature, another basic factor besides the microstructure. The temperature and temperature gradient of snow control water vapor diffusion through a snowpack. Temperature gradient, in its turn, depends on variations of near-surface air temperatures, solar radiation, and thermal properties of snow which change the temperature patterns and vapor contents. As snow cools down, condensation becomes more active whereby heat releases and the snow temperature rises; vice versa, warming of snow causes sublimation which consumes heat and leads to cooling. The energy output of sublimation and condensation and higher rates of these processes and vapor diffusion compared with conductive heat transfer smooth out the temperature curve [*Krass and Merzlikin, 1990*]. Therefore, the heat and mass transfer problem should be solved simultaneously with temperature field determination.

Mass transfer is modeled assuming full saturation of interstitial water vapor in a snowpack, while its density shows a unique temperature dependence. Therefore, the vapor density difference between the layers of a snowpack, related to temperature gradient, controls its diffusion [*Pavlov, 1979*]. The diffusion of water vapor is directed toward lower density, most often to the snow surface.

The effect of water vapor diffusion on mass transfer in a snowpack and on variability of thermal conductivity of snow was studied by numerical experiments. The 1D temperature distribution in a snowpack was found from the Fourier law [*Osokin et al., 2004a*]:

$$A\frac{\partial T_s}{\partial \tau} = \frac{\partial}{\partial z}\left(\lambda_s \frac{\partial T_s}{\partial z}\right) + F(z,\tau), \qquad (17)$$

where the coefficient

$$A = \rho_s c_s + L_e \frac{\partial e}{\partial T_s}$$

refers to the effect of vapor sublimation and condensation on snow temperature [*Krass and Merzlikin, 1990*], while

$$\lambda_s = \lambda_c + L_e D \frac{\partial e}{\partial T_s} \qquad (18)$$

is the thermal conductivity as a sum of components corresponding to conductive and convective heat transport [*Pavlov, 1962*].

Other variables in (17) are: T_s is the snow temperature, K; z is the coordinate along the snow depth; τ is the time; c_s is the snow heat capacity; λ_c is the conductive component of snow thermal conductivity λ_s; L_e is the specific heat of evaporation; D is the coefficient of water vapor diffusion in a snowpack; e is the density of saturated vapor; $F(z, \tau)$ is heat release at the account of hard solar radiation, assumed to be $F(z, \tau) = 0$.

Snow-air heat exchange on the snow surface is specified as

$$\lambda_s \frac{\partial T_s}{\partial z} = Q_\Sigma,$$

where $Q_\Sigma = Q_c + Q_e + Q_r$ is the total heat flux due to convection, evaporation, and effective radiation from the surface, respectively.

The conductive thermal conductivity λ_c used in (17) corresponds to the minimum thermal conductivity, and can be considered as the lower envelope of its range (equation 3).

To check this assumption, the thermal pattern of a snowpack was modeled for negative temperatures at which the vapor diffusion effect becomes vanishing. The thermal conductivity λ_c was estimated from measured snow temperatures below −30 °C at the Vostok station in Antarctica. The thermal conductivity based on measurements for 11 days [*Osokin et al., 2004b*] showed the best fit with λ_c calculations according to equation (3), while the difference between λ_c and λ_s was within 2 %. However, although λ_{sl} estimates found with (3) are of good quality for Antarctica, they give underestimated values for the greatest part of Russia. Therefore, λ_c was assumed to correspond to the thermal conductivity λ_{cP} estimated with (6) [*Pavlov, 1979*] in the further consideration.

Equation (17) and relationship (6) were used to estimate snow thermal conductivity variations in time and space (depth). Consider, for example, the case of a mean daily air temperature of −10 °C; a range of sine-shaped daily variations T_a of 15 °C; a 0 °C temperature at the base of a 0.5 m thick snowpack with a density of 250 kg/m^3; the water vapor diffusion in snow (D, m^2/s) is [*Pavlov, 1979*]

$$D(t_s) = 0.92\cdot10^{-4} + 0.29\cdot10^{-5} t_s + 0.56\cdot10^{-7} t_s^2.$$

Calculations were applied to estimate the snow temperature at different depths, water vapor diffusion, and snow thermal conductivity variations.

The variable $k_d = (\lambda_s - \lambda_c)/\lambda_s$ refers to the share of vapor diffusion heat transfer through a snowpack. Increase in k_d shows increasing contribution of water vapor diffusion to heat transport through a snowpack. According to calculations with this model, thermal conductivity of snow varies with depth and with time during a day, the difference reaching, respectively, 16–45 % and 25 % (Fig. 5).

As the calculations show, the share of water vapor diffusion k_d is lower in denser and colder snow (Fig. 6): as the density of snow increases from 150 to 400 kg/m^3, k_d decreases from 0.06 to 0.02 at −30 °C and from 0.40 to 0.17 at −4 °C, respectively.

Water vapor diffusion contributes more to heat transfer through snow as its temperature increases

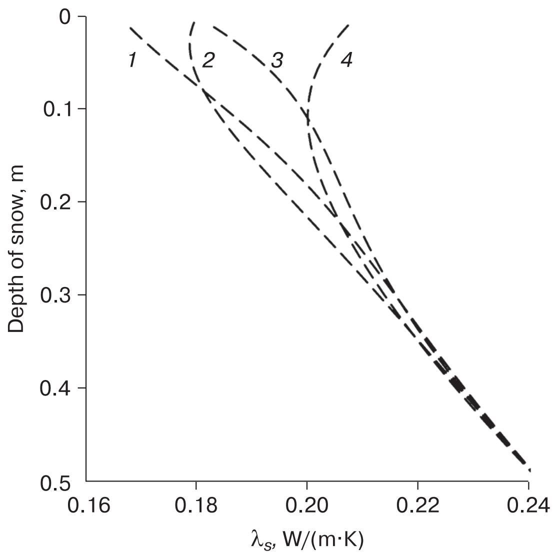

Fig. 5. Variations of snow thermal conductivity (λ_s) with depth at every 6 h, at daily temperature contrasts of −17.5 °C (*1*); −10 °C (*2*, *3*); −2.5 °C (*4*).

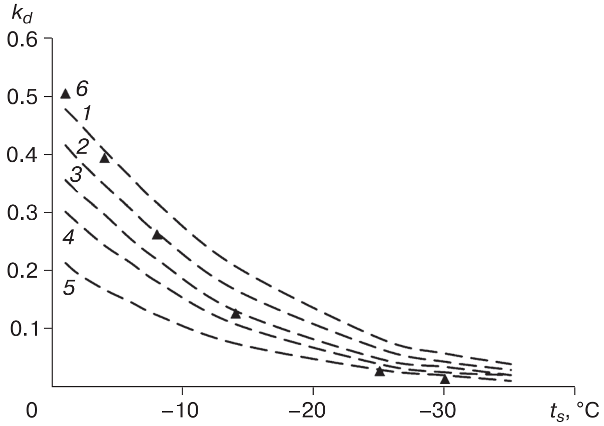

Fig. 6. Contribution of water vapor diffusion (k_d) to heat transfer through snow of densities 150 (*1*), 200 (*2*), 250 (*3*), 300 (*4*), and 400 kg/m³ (*5*); *6* – values obtained with equation of Pavlov (4).

from –30 to –4 °C: k_d increases from 0.06 to 0.40 in snow with a density of 150 kg/m³ and from 0.02 to 0.17 for 400 kg/m³.

EFFECT OF AIR CONVECTION ON SNOW THERMAL CONDUCTIVITY

Air convection is another component of thermal conductivity, besides water vapor diffusion. Interstitial air flows through snow cause significant effect on its thermal conductivity [*Yen, 1965; Albert, 1993; Colbeck, 1997*]. However, this heat transfer mechanism has been commonly attributed to horizontal pressure gradients on the snow surface and to ground temperature variations. The possible effect of air convection on the thermal conductivity of firn consisting of round ice grains was estimated using calculations by a method designed for a granular layer [*Aerov and Todes, 1968*].

Heat flux is given by $q = \lambda_c \Delta T/\Delta x + G c_t \Delta T$, and snow thermal conductivity is found as $\lambda_s = q/(\Delta T/\Delta x)$. The contribution of air convection to thermal conductivity is estimated as

$$\varphi = \lambda_s/\lambda_c = 1 + G c_t \Delta x/\lambda_c.$$

With estimates of the lifting force of an air flow and the hydraulic resistance of granular snow for a slow air flow, the contribution of air convection can be found as [*Aerov and Todes, 1968*]

$$\varphi - 1 = \beta_t \Delta T \varepsilon^2 \rho_a c_t \Delta x g/(2a^2 \rho \nu \lambda_c K),$$

where G is the mass speed of a convective air flow; β_t is the air thermal expansion; ε is the share of inner capillary volumes in the total layer volume; ρ_a is the air density; c_t is the air heat capacity; g is the acceleration due to gravity; $a = \pi d^2/(\pi d^3/6) = 6/d$ is the surface area of the granular snow layer per unit volume (d is the grain diameter); ν is the air kinematic viscosity;

Table 1. **Contribution of air convection (%) to thermal conductivity ($\varphi - 1$) at firn depth 0.5 m and a density of 520 kg/m³**

Temperature gradient in snow, °C/m	Grain size, mm			Air flow speed, mm/h
	1.0	1.5	2.0	
10	1.4	3.3	5.8	32
20	3.0	6.7	12.0	66
40	6.4	14.4	25.7	138
80	14.8	33.2	59.1	307

$K \approx 4.55$–5.00 is the resistance of granular snow; ΔT is the temperature difference at the distance Δx.

The term $\varphi - 1 = (\lambda_e - \lambda_c)/\lambda_c$ refers to the contribution of air convection flows to the thermal conductivity without regard to water vapor diffusion. Table 1 gives $\varphi - 1$ estimates for a 0.5 m thick firn layer having a density of 520 kg/m³ (cubic grain package) and a conductive thermal conductivity of 0.4 W/(m·K).

The calculations show that air convection may contribute considerably into the thermal conductivity of medium-grained dense firn: up to 6.7–14.4 % at a temperature gradient of 20–40 °C/m through a snowpack.

However, hydraulic resistance is unknown for snow of different types and densities, and further investigation is required to estimate the true role of air convection.

CONCLUSIONS

Heat transfer through a snowpack has multiple controls and proceeds by different mechanisms, including conduction heat transfer between ice crystals, diffusion of water vapor, and convective air flows. In the current practice, thermal conductivity of snow is estimated using empirical relationships, which have been compared in this study. The lower envelope of snow thermal conductivities estimated from twenty known regression curves corresponds to values we obtained in Antarctica for snow varying in temperature from –30 to –40 °C. The thermal conductivity of snow calculated with the relationship of Sturm is 5–10 % higher than that based on the lower envelope for the snow density range 250–400 kg/m³. The upper envelope of the thermal conductivity variance is close to the value obtained from the equation of Pavlov for a snow temperature of –1 °C.

Recent experimental investigation of the thermal conductivity of different snow types, with densities of 100 to 400 kg/m³, from the Moscow region yielded relationships for blown snow (density range of 190–310 kg/m³), new snow (80–170 kg/m³), and fine and coarse depth hoar (0.8–1.5 mm grain sizes, density 185–310 kg/m³ and 1–3 mm grains, 260–450 kg/m³, respectively).

The experimental results from the Moscow region show large influence of the snow microstructure on thermal conductivity. Namely, the thermal conductivity of granular snow is 21–36 % and 57–85 % higher than in blown snow and depth hoar, respectively.

According to modeling results, water vapor diffusion contributes more to heat transfer in less dense snow at small negative temperatures. Snow warming from –30 to –4 °C increases the share of vapor diffusion in heat transfer within a snowpack (k_d) from 0.06 to 0.40 and from 0.02 to 0.17 at snow densities of 150 kg/m^3 and 400 kg/m^3, respectively.

Thermal conductivity becomes 58 % and 28 % higher upon temperature increase from –30 to –4 °C in snow with densities 150 kg/m^3 and 300 kg/m^3, respectively.

The calculations suggest a significant contribution of air convection to thermal conductivity in dense granular snow, but further investigation is required to estimate this effect in other types of snow.

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