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SHORT NOTES

NEW DATA ON THE THERMAL CONDUCTIVITY OF NATURAL SNOW

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ABSTRACT. The thermal conductivity and diffusivity of natural snow computed from Fourier-type analyses of annual snow temperature variations are shown to be strongly temperature dependent. The computed temperature coefficients of −0.007 and −0.012 deg⁻¹ respectively, agree well with older laboratory experiments carried out on polycrystalline ice.

RÉSUMÉ. *Nouvelles données sur la conductivité thermique de la neige naturelle.* D'après les analyses par séries de Fourier des variations annuelles de la température de la neige, on montre que la conductivité et la diffusivité thermique de la neige naturelle dépendent beaucoup de la température. Les coefficients thermiques calculés égaux respectivement à 0,007 et −0,012 deg⁻¹, sont en bon accord avec des résultats de laboratoire plus anciens obtenus sur de la glace polycristalline.

ZUSAMENFASSUNG. *Neue Daten zur Warmeleitfahigkeit von naturlichem Schnee.* Die Wärmeleitfähigkeit und—durchlässigkeit natürlichen Schnees—berechnet aus Fourier-Analysen von jährlichen Änderungen der Schneetemperatur—erweisen sich als stark temperaturabhängig. Die errechneten Temperaturkoeffizienten von 0,007 bzw. 0,012 deg⁻¹ stimmen mit älteren Laborergebnissen, die an polykristallinem Eis durchgeführt wurden, gut überein.

THE thermal conductivity of pure polycrystalline ice at 0°C is approximately four times that of water at that temperature. The *International critical tables* contain two values for ice at 0°C which differ by 5%. Schofield and Hall (1927) selected a value of 2.20 W m⁻¹ deg⁻¹, whereas Van Dusen (1929) gave a value of 2.09 W m⁻¹ deg⁻¹. Subsequent measurements as listed by Powell (1958) have confirmed that the I.C.T. values are approximately correct and have suggested that crystal anisotropy could possibly account for the observed small differences. The position is much less satisfactory at lower temperatures where large differences exist between the results of Lees (1905) and Jakob and Erk (1929). The latter's results appear to be more reliable, since Dillard and Timmerhaus (1966) have reproduced these values experimentally and Ratcliffe's (1962) values also agree to within about 12% at −120°C with those of Jakob and Erk. All these values are for polycrystalline ice. Moreover, the thermal conductivity of many crystalline materials has been found to be proportional to the reciprocal of the absolute temperature within a certain temperature range (Euken, 1911). Such a relation down to 100 K is more nearly satisfied by the data of Jakob and Erk than those of Lees, and also fits the data of Dillard and Timmerhaus and of Ratcliffe. Recently, Fletcher (1970) has described a "hump" effect in the temperature relationship at low temperatures, which has also been acc

experiments carried out on polycrystalline ice.

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at depths where non-conductive processes of heat transfer were shown to be negligible. By comparing these results, listed in the table below, with mean weighted values of a series of measurements close to the freezing point, taken from Mellor (1964), the temperature coefficients of the thermal conductivities and diffusivities could be deduced. They are assumed to be linear over the temperature range considered, as shown approximately by the laboratory results of Jakob and Erk (1929), Dillard and Timmerhaus (1966), and Ratcliffe (1962). Changes of specific heat of the ice with temperature were taken from Dorsey (1940).

Table I. Thermal properties of ice

Density	*Temperature T*	*Thermal conductivity at T*	*Thermal conductivity at 0°C*	*Temperature coefficient*	*Thermal diffusivity at T*	*Thermal diffusivity at 0°C*	*Temperature coefficient*
$Mg\ m^{-3}$	°C	$W\ m^{-1}\ deg^{-1}$	$W\ m^{-1}\ deg^{-1}$	deg^{-1}	$m^2\ s^{-1}$	$m^2\ s^{-1}$	deg^{-1}
0.42	−60	0.71	0.50	−0.0070	0.96×10^{-6}	0.53×10^{-6}	−0.0135
0.57	−17	0.91	0.82	−0.0065	0.94	0.80	−0.0103
0.917	−60	3.11	2.22	−0.0067	1.99	1.18	−0.0114
				Mean: −0.0067			Mean: −0.0117

There is reasonable agreement between the temperature coefficients at different densities, and this further confirms the values obtained by Jakob and Erk.

The temperature dependence of the thermal properties can be seen to be anything but negligible, even for small temperature changes near the freezing point. This is usually not considered in heat-flux computations in ice and snow and may lead to considerable errors.

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REFERENCES

Dalrymple, P. C., *and others*. 1966. South Pole micrometeorology program: data analysis, [by] P. C. Dalrymple, H. H. Lettau, S. H. Wollaston. (*In* Rubin, M. J., *ed*. *Studies in Antarctic meteorology*. Washington, D.C., American Geophysical Union, p. 13–57. (Antarctic Research Series, Vol. 9.))

Dillard, D. S., *and* Timmerhaus, K. D. 1966. Low temperature thermal conductivity of solidified H_2O and D_2O. *Pure and Applied Cryogenics*, Vol. 4, p. 35–44.

Dorsey, N. E. 1940. *Properties of ordinary water-substance in all its phases: water-vapor, water and all the ices*. New York, Reinhold Publishing Corporation. (American Chemical Society. Monograph Series, No. 81.)

Euken, A. 1911. Über die Temperaturabhängigkeit der Wärmeleitfähigkeit fester Nichtmetalle. *Annalen der Physik*, Vierte Folge, Bd. 34, Ht. 2, p. 185–221.

Fletcher, N. H. 1970. *The chemical physics of ice*. Cambridge, University Press. (Cambridge Monographs on Physics.)

Jakob, M., *and* Erk, S. 1928. Wärmedehnung des Eises zwischen 0 und −253°. *Zeitschrift für die gesamte Kälteindustrie*, Bd. 35, p. 125–30.

Klinger, J., *and* Neumaïer, K. 1969. Conductibilité thermique de la glace. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* (Paris), Sér. B, Tom. 269, No. 19, p. 945–48.

Lees, C. H. 1905. Effect of temperature on thermal conductivities of electrical insulators. *Philosophical Transactions of the Royal Society*, Ser. A, Vol. 204, Art. 12, p. 433–66.

Mantis, H. T., *ed*. 1951. Review of the properties of snow and ice. *U.S. Snow, Ice and Permafrost Research Establishment. Report* 4.

Mellor, M. 1964. Properties of snow. U.S. Cold Regions Research and Engineering Laboratory. *Cold regions science and engineering*. Hanover, N.H., Pt. III, Sect. A1.

Powell, R. W. 1958. Thermal conductivities and expansion coefficients of water and ice. *Advances in Physics*, Vol. 7, No. 26, p. 276–97.

Ratcliffe, E. H. 1962. The thermal conductivity of ice: new data on the temperature coefficient. *Philosophical Magazine*, Eighth Ser., Vol. 7, No. 79, p. 1197–203.

Schofield, F. H., *and* Hall, J. A. 1927. Thermal insulating materials for moderate and low temperatures. (*In* Washburn, E. W., *ed*. *International critical tables of numerical data, physics, chemistry and technology*. New York and London, McGraw-Hill. Vol. 2, p. 312–16.)

Schwerdtfeger, P. 1963. Theoretical derivation of the thermal conductivity and diffusivity of snow. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Assemblée générale de Berkeley, 19-8—31-8 1963. Commission des Neiges et des Glaces*, p. 75-81.

Schytt, V. 1960. Glaciology. II. Snow and ice temperatures in Dronning Maud Land. *Norwegian-British-Swedish Antarctic Expedition, 1949-52. Scientific Results*, Vol. 4, D, p. 153-79.

Van Dusen, M. S. 1929. Thermal conductivity of non-metallic solids. (*In* Washburn, E. W., *ed. International critical tables of numerical data, physics, chemistry and technology*. New York and London, McGraw-Hill. Vol. 5, p. 216-17.)

Weller, G. E., *and* Schwerdtfeger, P. 1970. Thermal properties and heat transfer processes of the snow of the central Antarctic plateau. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique.*] [*International Council of Scientific Unions. Scientific Committee on Antarctic Research. International Association of Scientific Hydrology. Commission of Snow and Ice.*] *International Symposium on Antarctic Glaciological Exploration (ISAGE), Hanover, New Hampshire, U.S.A., 3-7 September 1968*, p. 284-98.