SPECTRAL OPTICAL PROPERTIES OF PURE ICE AND SNOW

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Following from: *Solar heating and melting of snowpacks and ice sheets in polar regions*

Optical constants of ice in the visible and near-infrared

Two spectral optical constants are usually considered as real and imaginary parts of the complex index of refraction, $m(\lambda) = n(\lambda) - i\kappa(\lambda)$, where n is the index of refraction and κ is the index of absorption (Born and Wolf 1999). Spectral behavior of the indices of refraction and absorption are not independent of each other but satisfy the Kramers–Krönig relation (Lucarnini et al. 2005). Particularly, the index of refraction is almost constant in the spectral ranges of a very low absorption as that for water ice in the visible range. The spectral optical constants of ice obtained by Warren and Brandt (2008) are plotted in Fig. 1. The wavelength range shown in this figure is ~~the~~ important not only for the radiative heating problem under consideration but also for some problems related with the UV radiation.

The extremely low value of κ in the visible and a significant increase of absorption index in the near-infrared range determine the specific spectral properties of ice grains and snow in these spectral ranges. In particular, the known high value of snow albedo is a result of almost perfect spectral transparency of pure ice (Wiscombe and Warren 1980, Warren 1982, Kokhanovsky and Zege 2004). Obviously, even very small impurities such as atmospheric aerosol particles may increase significantly the value of κ, and this strongly affects the observed albedo of snow. One can also recommend several recent papers on the specific problem of snow albedo: Gardner and Sharp (2010), Brandt et al. (2011), Malinka et al. (2016), Wang et al. (2017), Kokhanovsky et al. (2018), Picard et al. (2020), He and Flanner (2020).

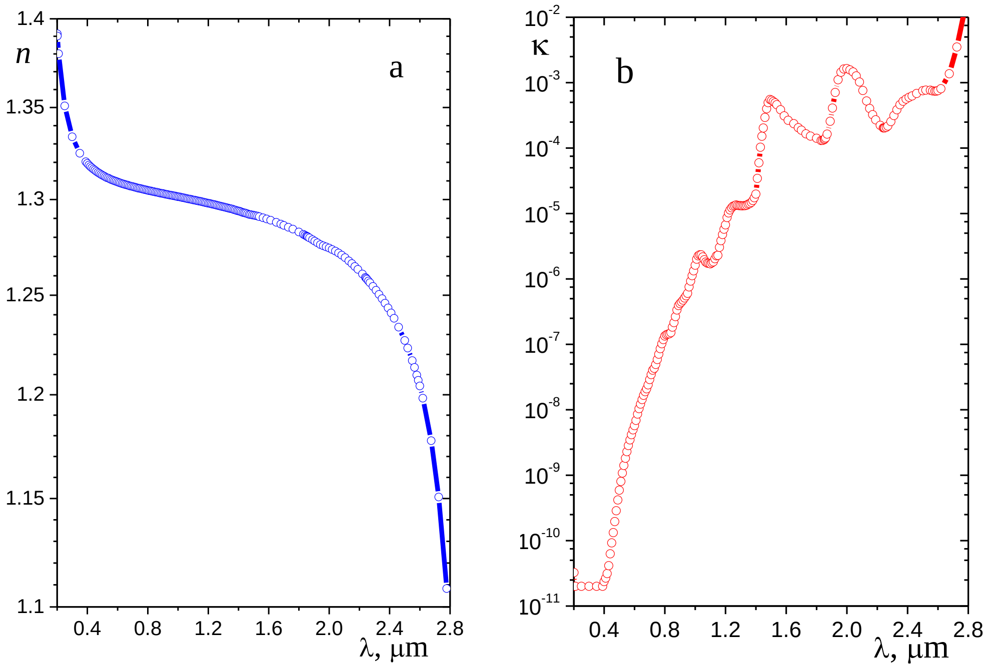

Figure 1. Spectral optical constants of ice: a – index of refraction, b – index of absorption.

Optical properties of snow

Theoretical modeling of optical properties of various turbid media is often based on the classical Mie theory for spherical particles (Van de Hulst 1981, Bohren and Huffman 1983, Hergert and Wriedt 2012). The size of the snow particles is much greater that the wavelength of solar radiation, and the shape of these particles may be very complex. Therefore, the geometrical optics (GO) approximation and some other advanced methods are used to calculate optical properties of single particles and the resulting properties of snow (Bi et al. 2011, Borovoi et al. 2014, Lindqvist et al. 2018). Alternative approaches for optical properties of ice grains of complex shape can be found in papers (Grenfell and Warren 1999, Neshyba et al. 2003, Libois et al. 2013, Räisänen et al. 2015, Ishimoto et al. 2018). However, for the sake of simplicity, one should not forget about physically sound analytical approximations suggested in early papers by Irvine (1963, 1964), Kokhanovsky and Zege (1995, 1996), Dombrovsky (1996), and Dombrovsky and Baillis (2010).

In the present article, the spherical ice grains of different size are considered instead of ice particles of complex shape and orientation. The calculations are performed for ice grains of radius $a = 50$ μm, 100 μm, and 200 μm. These variants can be treated as those corresponding to different snow morphology. The case of nonspherical particles can be treated as well. However, the present study is focused on snowpack heating and the problem of nonsphericity of ice grains is of a secondary importance.

The most general solution for the optical properties of homogeneous spherical particles is given by the rigorous Mie theory. However, the ice grains considered are much greater in size than the wavelength. This makes it reasonable to consider the GO approximation as the main tool in this work. At the same time, the Mie theory with the use of computer code published in (Dombrovsky 1996) and described also by Dombrovsky and Baillis (2010) is used for the reference calculations.

With the use of transport approximation, only two dimensionless characteristics of absorption and scattering of single particles are necessary: the absorption efficiency factor, Q_a, and the transport efficiency factor of scattering, $Q_{\mathrm{s}}^{\mathrm{tr}} = Q_{\mathrm{s}} \times (1 - \bar{\mu})$, where $\bar{\mu}$ is the asymmetry factor of scattering. The values of transport efficiency factor of extinction, $Q_{\mathrm{tr}} = Q_a + Q_{\mathrm{s}}^{\mathrm{tr}}$, and transport albedo of the particle, $\omega_{\mathrm{tr}} = Q_{\mathrm{s}}^{\mathrm{tr}}/Q_{\mathrm{tr}}$ are also considered. The mentioned characteristics depend on spectral optical constants and also on the diffraction parameter $x = 2\pi a/\lambda$ introduced in the Mie theory.

The results of calculations using the GO solution obtained by Kokhanovsky and Zege (1995) are compared with calculations based on the Mie theory in Fig. 2. One can see that GO can be used to calculate both Q_a and ω_{tr} for ice grains of various size. As a result, the important value of transport extinction coefficient, $Q_{\mathrm{tr}} = Q_a/(1 - \omega_{\mathrm{tr}})$, can be also obtained using the GO solution for the case of $\kappa << n$:

$$Q_a = 2 - Q_{\mathrm{s}} \quad Q_{\mathrm{s}} = 1 + \tilde{Q}_{\mathrm{s}} \quad \bar{\mu} = (1 + y)/\left(1 + \tilde{Q}_{\mathrm{s}}\right) \tag{1a}$$

$$\tilde{Q}_{\mathrm{s}} = \frac{1}{2}\sum_{j=1}^{2} \int_0^{\pi/2} f_{\mathrm{j}}(\zeta)\, sin\, 2\,\zeta\, \mathrm{d}\zeta \quad y = \frac{1}{2}\sum_{j=1}^{2} \int_0^{\pi/2} \frac{\varphi_{\mathrm{j}}(\zeta)\, sin\, 2\zeta\, \mathrm{d}\zeta}{1 - 2R_{\mathrm{j}}\tilde{E} + R_{\mathrm{j}}^2 \tilde{E}^2} \tag{1b}$$

where

$$\varphi_{\mathrm{j}}(\zeta) = \tilde{E}\left(1 - R_{\mathrm{j}}\right)^2 cos\, 2\left(\zeta - \tilde{\zeta}\right) + R_{\mathrm{j}}\left(1 - \tilde{E}^2\right) cos\, 2\,\zeta + 2R_{\mathrm{j}}^2\left(\tilde{E} - cos\, 2\,\tilde{\zeta}\right)\tilde{E}\, cos\, 2\,\zeta \tag{1c}$$

$$f_{\mathrm{j}}(\zeta) = R_{\mathrm{j}} + \tilde{E}\left(1 - R_{\mathrm{j}}\right)^2/\left(1 - R_{\mathrm{j}}\tilde{E}\right) \tag{1d}$$

$$R_1 = \frac{tan^2(\zeta - \tilde{\zeta})}{tan^2(\zeta + \tilde{\zeta})} \quad R_2 = \frac{sin^2(\zeta - \tilde{\zeta})}{sin^2(\zeta + \tilde{\zeta})} \quad \tilde{E} = exp\left(-4\kappa x\sqrt{1 - \tilde{\zeta}^2}\right) \quad \tilde{\zeta} = \frac{cos\, \zeta}{n} \tag{1e}$$

To avoid numerical errors of direct calculations by Eqs. (1a)–(1e) at $Q_a < 10^{-5}$, one can use the following approximation which is correct in the case of $\kappa x << 1$:

$$Q_a = 4\nu\kappa x \quad \nu = \frac{2}{3}\left[n^3 - (n^2 - 1)^{3/2}\right] \tag{2}$$

An approximation suggested by Dombrovsky (2002) for arbitrary values of x is also appropriate.

One can see in Fig. 2b that light scattering highly predominates very weak absorption in the visible spectral range. This results in a strong reflection of visible solar radiation from the snow surface and relatively small contribution of this spectral range to the heating of snow surface layer. At the same time, the remaining (not reflected) visible part of the collimated solar radiation forms almost diffuse radiation field in the snow. As a result, the visible light is absorbed relatively far from the snow surface, and its contribution to heating deep layers of snow is considerable. On the contrary, the reflection of near-infrared solar radiation from the snow surface is relatively small and this spectral range contributes strongly to the radiation power absorbed in the surface layer.

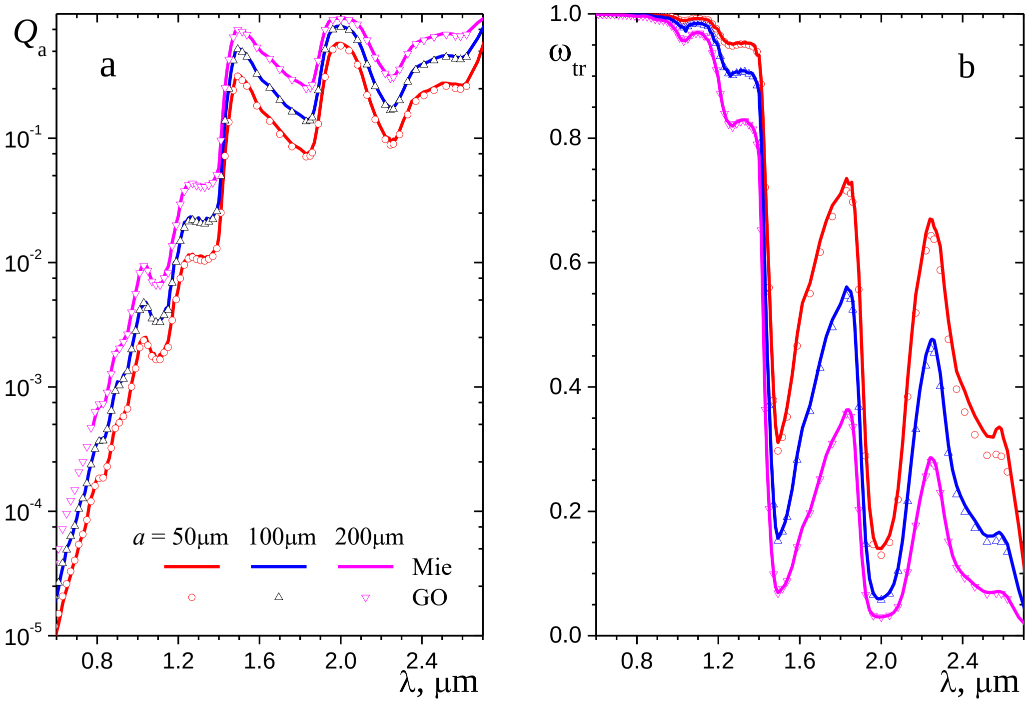

Figure 2. Optical properties of ice grains: a – efficiency factor of absorption, b – transport albedo.

It is assumed that the hypothesis of independent scattering by single ice grains in snow is true (Mishchenko, 2018). It means that each particle absorbs and scatters the radiation in exactly the same manner as if other particles do not exist. In addition, there is no systematic phase relation between partial waves scattered by individual particles during the observation time interval, so that the intensities of the partial waves can be added without regard to phase. In other words, each particle is in the far-field zones of all other particles and scattering by individual particles is incoherent.

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