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© *Э. П. Зеге*[1], *А. В. Малинка*[1], *И. Л. Кацев*[1], *А. С. Прихач*[1], *Л. Истомина*[2], *Г. Хейгстер*[2], *Г. Сприн*[2]
[1]Институт физики им Б. И. Степанова НАН Беларуси, г. Минск, Беларусь
[2]Институт физики окружающей среды, Бременский Университет, Германия
ellazege@gmail.com

ОТРАЖАТЕЛЬНЫЕ СВОЙСТВА АРКТИЧЕСКОГО ЛЕТНЕГО ЛЬДА В ВИДИМОМ И ИНФРАКРАСНОМ ДИАПАЗОНАХ

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Представлен краткий обзор работ авторов, в которых развита аналитическая теория спектральных оптических характеристик различных типов морского льда как рассеивающей среды (коэффициентов ослабления и поглощения, индикатрисы рассеяния), а также модели отражения ледовым покрытием в Арктике. Лед моделируется как статистически однородная случайная смесь лед-воздух-вода с крупным (по сравнению с длиной волны излучения) масштабом неоднородностей. Параметры смеси (концентрации и размеры неоднородностей) определяются генезисом и положением слоев льда. Во всех случаях масштаб неоднородностей много больше длины волны света. Для определения оптических характеристик различных типов морского льда развиты теории рассеяния света стохастической смесью в приближениях геометрической оптики и Вентцеля—Крамерса—Бриллюэна. Спектральное отражение ледовыми полями описывается в рамках асимптотической теории распространения света в оптически толстых слабопоглощающих слоях. Для описания оптических характеристик тающего (летнего) льда развита модель отражения света прудом талой воды на льду (снежницей). Таким образом определяются все оптические характеристики арктического льда, которые необходимы в качестве входных данных для расчёта переноса излучения. Показано хорошее совпадение полученных результатов с данными измерений, выполненных в ряде арктических экспедиций. Развиты методы атмосферной коррекции спутниковых и полевых данных.

Ключевые слова: арктический морской лед, таяние, отражение света, оптические характеристики льда, рассеяние света.

E. Zege[1], *A. Malinka*[1], *I. Katsev*[1], *A. Prikhach*[1], *L. Istomina*[2], *G. Heygster*[2], *G. Spreen*[2]
[1]Institute of Physics, NAS of Belarus, Minsk
[2]Institute of Environmental Physics, University of Bremen, Bremen

REFLECTIVE PROPERTIES OF SUMMER ARCTIC SEA ICE IN VISIBLE AND NEAR INFRARED

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This article presents a brief overview of the recent authors' works where analytical solutions for the reflection characteristics of summer ice floes with melt ponds in the Visible and near IR have been developed, checked with field experiments and discussed. Sea ice is considered as a statistically homogeneous random mixture of ice, air, and water with a large (in comparison with the light wavelength) scale of inhomogeneities. Within the framework of stereology the inherent scattering characteristics (the attenuation and absorption coefficients, scattering phase functions) of various types of sea ice have been specified analytically. Spectral reflection by ice layers is described within the asymptotic approach of the radiative transfer theory of light propagation in optically thick and comparatively weakly absorbing layers. During melting period the surfaces of ice floes are covered by so called white ice and melt ponds in different proportions. The main factor determining the pond reflection is reflection of its bottom ice. The spectral-angular characteristics of the reflection by both these components (white ice and melt ponds) of Arctic summer ice floes are presented. It is shown that the obtained results are in good agreement with the measurements made in a number of Arctic expeditions, the developed methods of atmospheric correction, which is necessary for processing of both Arctic satellite and field data, being used.

Key words: arctic sea ice, melting, light reflectance, ice optical properties, scattering.

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1. Introduction. The scientific community is deeply concerned about the acceleration of the ice melting process in the Arctic. It is difficult to estimate its after-effects. Monitoring the state of the Arctic sea ice is of primary importance for understanding global climate changes, as well as for the started fast development of Arctic navigation and oil industry, changes in the world logistics and etc. The special concern of the scientific community to the ice optics exists, particularly, because just the knowledge of the satellite measured spectral response of ice cover to solar illumination allows users to monitor, interpret, and deploy the information about an ice situation in the difficult to access polar regions.

The systematic investigations of reflection characteristics of the summer ice in the Arctic have been carried out since beginning of the 20th century. In summer, during melting period the ice floes are covered by highly scattering top layer, known as “white ice” [1—2]. Note that the term “white ice” could not be found in any catalog of the sea ice types (see for instance [3]). *White ice* is a layer covering the ice floe surface, some coverlet, formed after melt water has drained off from the surface elevations into the depressions producing *melt ponds*. White ice consists of ice grains with the order of millimeters in size and, thus, can be described within the same approach as snow, but with larger grains. Just this strongly scattering layer gives the main contribution to the ice floe reflection in Visible and near IR. The summer ice melting has been studied carefully [4—10] and the empirical description of the white ice microstructure and its reflection properties was summarized and presented in the monograph [2].

During polar summer melt ponds typically occupy 20—40 % of the Arctic sea ice surface [11—13]. Maximal reported values of melt ponds fraction are up to 60 % on multiyear ice [14] and up to 80 % on landfast ice [15]. Melt ponds reduce the ice albedo significantly speeding up the process of melting, amplifying the positive ice-albedo feedback effect [16].

The proportion of the white ice cover and melt ponds fractions at the ice floes governs albedo of the ice floes and process of ice summer melt. Although there are quite a lot of measurements of white ice and melt pond spectral albedo [1, 2, 8, 17—20], an adequate physical and optical model of summer ice floe reflection, including reflection from white ice and melt ponds, has been still absent. Particularly, there is no theoretical solution either for optical characteristics of white ice, or for reflection of ice floes with melt ponds. Even though Makshtas and Podgorny [21] gave the analytical formula for the pond albedo in terms of the albedo of its bottom, the problem of calculation of the bottom albedo was not addressed.

For last several years the authors have been developing the theory of optical properties and spectral-angular reflection characteristics of summer sea ice in the framework of the theory of light scattering in turbid media and radiative transfer theory [22—25]. In this paper we present the essence of the developed model of the reflective properties of summer melting ice with melt ponds. Optical characteristics of white ice are described in the framework of the geometrical optics for the random mixture of ice and air [22], while the WKB approximation is deployed in the case of irregularly shaped particles for brine inclusions in ice [23]. The spectral range considered is visible and near infrared. The equations for spectral-angular reflective characteristics of ice floes for areas covered by white ice, snow and melt ponds were developed and checked with the field measurements performed during field campaigns in the Arctic (SHEBA-1998, Barrow-2008, and Polarstern-2012) [24—25].

This paper is written as a review for experts in various areas concerning different aspects of exploring the Arctic Ocean. It presents the essence of the developed model of the reflective properties of summer melting ice with melt ponds. The paper is arranged as follows. First, light scattering by white ice is described in Sec. 2 with subsection 2.1 introducing the inherent optical properties (IOPs) of white ice and Sec. 2.2 considering ice floe reflection characteristics. Sec. 2.3 demonstrates examples of the field verification of the developed theory. The reflection by melt ponds is considered in Sec. 3. A simple optical model of melt pond reflection and an equation for the bottom albedo with a few physical characteristics are presented in Sec 3.1 and 3.2, correspondingly. Then Sec. 3.3 demonstrates some examples of the verification of the developed model with three datasets of *in-situ* measurements (SHEBA-1998, Barrow-2008, and Polarstern-2012). The conclusion sums up the paper.

2. Solar light reflection by white ice

2.1. Light scattering characteristics of white ice. The used optical model of white ice is a random mixture of ice and air [22, 24] with the spectral characteristics determined by the complex refractive index of ice $m = n + i\kappa$ and the mean chords of ice a and air h components ($a >> \lambda, \quad h >> \lambda$). The main inherent optical properties (IOPs) used in the radiative transfer theory and hydro-optics are the extinction coefficient ε, the single scattering albedo (photon survival probability) ω_0, and the scattering phase function $p(\theta)$.

It is shown in [22] that for the random mixture, to which the laws of geometrical optics are applicable, these values are equal to:

$$\varepsilon = \frac{1}{a+h}, \qquad \omega_0 = 1 - \frac{x T_{diff}}{x + T_{diff}}, \tag{1}$$

with $x = \alpha n^2 a$, where $\alpha = 4\pi\kappa/\lambda$ is the absorption coefficient of ice, and T_{diff} is the Fresnel transmittance through the air-ice boundary for diffuse light:

$$T_{diff} = \frac{2(5n^6+8n^5+6n^4-5n^3-n-1)}{3(n^3+n^2+n+1)(n^4-1)} + \frac{n^2(n^2-1)^2}{(n^2+1)^3}\ln\frac{n+1}{n-1} - \frac{8n^4(n^4+1)}{(n^4-1)^2(n^2+1)}\ln n. \tag{2}$$

The analytical expression for the phase function is given in [24]. Fig. 1, *a* presents the phase functions for white ice for wavelength 380 and 700 nm (the edges of the visible range) and in SWIR (2 µm). The phase functions are similar in the forward scattering region for all the wavelengths in the considered range and are practically independent of wavelength in the visible. The only parameter of the scattering phase function used in the presented theory is the average cosine of the phase function

$$g = \langle\cos\theta\rangle = \frac{1}{2}\int_0^{\pi} p(\theta)\cos\theta\sin\theta\, d\theta = \frac{1}{\omega_0}\left(r_1 + \frac{n^2 t_1^{\,2}}{T_{diff}(1-n^2) - r_1 + n^4(1+\alpha a)} \right), \tag{3}$$

where r_1 and t_1, like the value T_{diff}, are simple but cumbersome functions on real part of ice refractive index *n* and, hence, on λ only (full equations are given in [24]). The table presents values of T_{diff}, t_1, and r_1 in the range 0.3—1.1 µm.

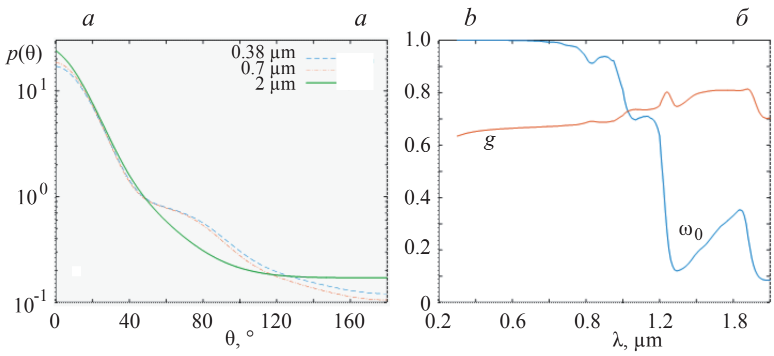

Fig. 1. Simulated phase functions (*a*) and spectral dependence of the single scattering albedo and the average cosine (*b*) for white ice with the mean chord of 2 mm.

Рис. 1. Рассчитанные индикатрисы рассеяния для трех длин волн (*а*) и спектральные зависимости альбедо однократного рассеяния и среднего косинуса (*б*) для белого льда со средним размером неоднородности 2 мм..

Spectral values of T_{diff}, t_1, and r_1

Спектральные значения T_{diff}, t_1 и r_1

λ (µm)	T_{diff}	t_1	r_1
0.3	0.9335	0.8991	0.0360
0.4	0.9358	0.9031	0.0355
0.5	0.9368	0.9048	0.0352
0.6	0.9374	0.9058	0.0351
0.7	0.9378	0.9065	0.0350
0.8	0.9381	0.9070	0.0349
0.9	0.9384	0.9075	0.0348
1.0	0.9386	0.9080	0.0348
1.1	0.9389	0.9085	0.0347

The example of the spectral dependence of the single scattering albedo ω_0 (eqs. (1), (2)) and the average cosine *g* (eqs. (2), (3)) for the "ice-air" random mixture with *a* = 2 mm is shown in fig. 1, *b*. It is seen that the medium is practically non-absorbing in the visible and near IR range (the photon arrival probability is greater than 0.9 in the interval 0.3—1.1 μm), which justifies the name "white ice". The average cosine *g* takes the values from 0.63 at 0.3 μm to 0.69 at 1.1 μm for *a* = 2 mm, with the mean value of about 0.67.

The spectral absorption of the white ice is mainly determined by the imaginary part of the refractive index. In the case of ice it has a pronounced minimum at about 0.3—0.4 μm. However, the careful analysis of the albedo field measurements, as well as of the satellite data, shows the presence of some absorbing contaminant. The observed spectral deformation for all available data can be described by the presence of the yellow substance (dissolved organic matter from the sea water).

With this in view we take

$$\alpha(\lambda) = \frac{4\pi}{\lambda}\kappa(\lambda) + \alpha_y(\lambda), \tag{4}$$

where $\alpha_y(\lambda)$ is the spectrum of the yellow substance, according to the model of Bricaud et al [26] with the corrections of *Kopelevich et al.* [27]:

$$a_y(\lambda) = \begin{cases} a_y(390)\exp\left[-0.015(\lambda-390)\right], & \lambda \le 500, \\ a_y(390)\exp\left[-0.015(500-390) - 0.011(\lambda-390)\right], & \lambda > 500. \end{cases} \tag{5}$$

The presence of the yellow substance in both Arctic and Antarctic ice was reported by many authors [28, 29]) and displayed in the shape of most of the field-registered reflection spectra we have analyzed. Once the more detailed data on the ice contaminants are available, their absorption spectra can be easily incorporated into the model through eq. (4).

2.2. Reflectance of white ice. The IOPs of ice floe change with depth. However, just white ice (the upper scattering layer) mainly determines the ice floe reflection during melting period. Moreover, the ice layer just below the white ice contains a lot of air inclusions [6] and shows the similar spectral behavior. Therefore, the reflective properties of a whole ice sheet could be considered just as those of the scattering layer with some effective parameters that take into account the effect of the lower layers.

The following apparent optical properties (AOPs) – the BRF (bidirectional reflectance factor) R, the albedo at direct incidence $r(\theta_0)$, a.k.a. the directional–hemispherical reflectance, and the albedo at diffuse incidence r_d, a.k.a. the bihemispherical reflectance — are used in various applications. The BRF depends on the zenith angles of incidence and observation (θ_0 and θ) and the azimuth φ between them. Also all the AOPs are spectrally dependent.

Describing the spectral reflection from an ice floe covered by white ice we proceed from the classical structural formulas for reflection and transmission by optically thick scattering layers [30—33]. This approach was used to describe reflection from snow and for an algorithm for satellite snow monitoring [34, 35].

Unlike a snow cover, white ice has the albedo of about 0.7—0.8 (or even less) in the blue-green region, what means that its optical thickness τ is finite. As a consequence, the optical thickness τ is the main parameter that determines its reflection and transmission of an ice floe. The following solution for the BRF of an optically thick layer of white ice, applicable for the spectral range of 0.3—0.8 μm was given in [24]:

$$R(\mu,\mu_0,\varphi) = R_\infty^0(\mu,\mu_0,\varphi)\frac{\sinh\left(\gamma\tau + y\left[1 - G(\mu)G(\mu_0)/R_\infty^0(\mu,\mu_0,\varphi)\right]\right)}{\sinh\left(\gamma\tau + y\right)} \tag{6}$$

Here $R_\infty^0(\mu,\mu_0,\varphi)$ is the BRF of a semi-infinite layer without absorption ($\mu = \arccos\theta,\ \mu_0 = \arccos\theta_0$),

$$G(\theta) = \frac{3}{7}(1+2\mu), \quad y = 4\sqrt{\frac{(1-\omega_0)}{3(1-\omega_0 g)}}, \quad \gamma = \sqrt{3(1-\omega_0)(1-\omega_0 g)}\,.$$

Eq. (6) was successfully verified numerically with the radiative transfer code RAY [36] and was used in the Arctic ice remote sensing technique [37, 38].

The spectral dependence of reflectance is defined by the single scattering albedo ω_0 determined by the complex refractive index of ice and the absorption of various possible pollutants including natural ones (adsorbed yellow substance, algae) or possible technogenic pollutions. The analysis of field data shows [24] that if one considers ice disposed far from a coastline, the spectral dependence of reflectance is described well by adding the absorption of yellow organic pigments from seawater.

Thus, the BRF of white ice is completely determined by following three parameter: the optical depth τ of a layer, the mean effective grain size a, and the absorption coefficient α_y of yellow pigments, which could arrive in white ice due to organics from seawater.

2.3. Verification with the field data. The described model of the summer ice reflection was verified with the reflectance spectra of white ice measured for various melting ice situations during the R/V Polarstern cruise ARK-XXVII/3, 2 August—8 October 2012 [38]. The mechanisms of sea ice melt pond formation end evolution. Particular attention was given to the correct account of the illumination conditions [24, 39]. Fig. 2 presents an example of the comparison of the measured reflectance spectra to the simulated ones. The spectral albedo of white ice is considered for two cases: when the ice surface is clean (fig.2, *a*) and when the significant presence of yellow organic matter with spectral absorption given by eq.(5) is displayed (fig.2, *b*). The presence of yellow substance is evident from the reduction of the albedo in the blue region. In both cases the coincidence of the measured and simulated data is excellent. A data set of the measured vs. simulated ice reflectance spectra are available in [40].

In general, the analysis of the experimental data shows that the model developed describes excellently the reflective properties of white ice and snow, at least as regards the spectral albedo. Moreover, it is quite satisfactory also in the cases that stand out of the initial frames of the model, such as wet ice/snow, crusted snow, frozen cracks, and snow covered ponds.

3. Reflection by melt ponds

3.1. Radiance reflected by a melt pond. The melt pond is modelled as a plane-parallel layer of pure water upon a layer of sea ice (the pond bottom). A ray inside the pond is attenuated according to the exponential law. We assume that the pond bottom reflects light by the Lambert law (the reflected radiance is independent of the direction). Makshtas and Podgorny [21] give the following formula for the albedo of a pond that satisfies the abovementioned assumptions:

$$A(\mu_0) = R^F(\mu_0) + T^F(\mu_0)\exp\left(-\frac{\varepsilon_w z}{\mu_0^w}\right)\frac{f_{out}(\varepsilon_w z)A_b}{n^2\left(1 - A_b f_{in}(\varepsilon_w z)\right)}, \tag{7}$$

where $R^F(\mu_0)$ and $T^F(\mu_0)$ are the Fresnel reflectance and transmittance of the water surface for incidence angle $\theta_0 = \arccos\mu_0$, n is the refractive index of water, μ_0^w is the cosine of the refractive angle, z is the pond depth, A_b is the pond bottom albedo, and ε_w is the extinction coefficient of water, equal to the sum of the water absorption (α_w) and scattering (σ_w) coefficients.

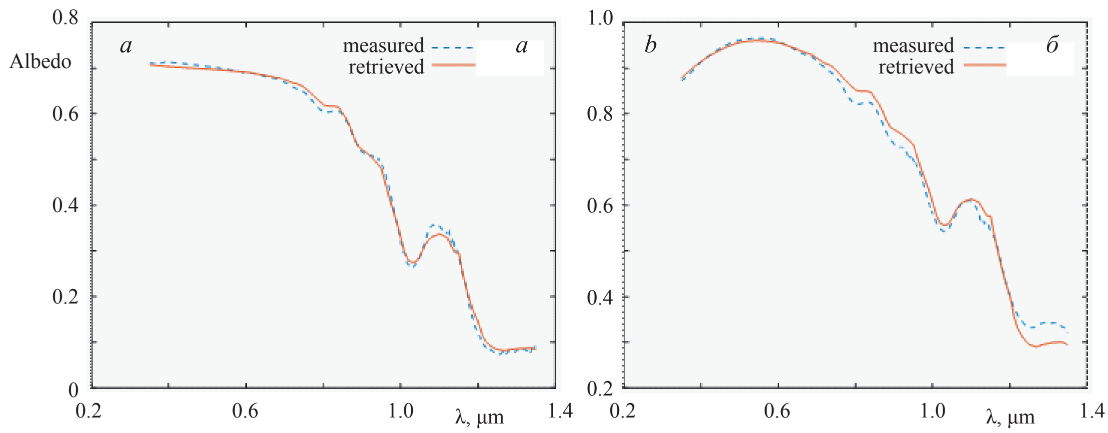

Fig. 2. Measured (*dashed*) and retrieved with Eq. (6) (*solid*) spectral albedo of pure white ice (*a*) and of ice polluted with yellow organic pigments (*b*).

Рис. 2. Измеренные (*пунктир*) и восстановленные по формуле (6) (*сплошная*) спектры альбедо белого льда: чистого (*а*) и загрязнённого жёлтым органическим пигментом (*б*).

Functions $f_{in}(x)$ and $f_{out}(x)$ are defined as:

$$f_{in}(x) = 2\int_0^1 R_{in}(\mu^w)\exp\left(-2\frac{x}{\mu^w}\right)\mu^w d\mu^w, \quad f_{out}(x) = 2\int_0^1 T^F(\mu)\exp\left(-\frac{x}{\mu^w}\right)\mu\, d\mu. \tag{8}$$

The expression for the melt pond BRF is derived from eq. (7) [25]:

$$R(\mu,\mu_0,\varphi) = \frac{\pi}{\mu_0}R^F(\mu_0)\delta(\mu-\mu_0)\delta(\varphi) + \frac{T^F(\mu)T^F(\mu_0)A_b}{n^2\left(1-A_b f_{in}(\varepsilon_w z)\right)}\exp\left(-\frac{\varepsilon_w z}{\mu_0^w}-\frac{\varepsilon_w z}{\mu^w}\right). \tag{9}$$

The first terms in eqs. (7) and (9) describe the solar specular reflection from the water surface, while the second one describes the light, multiply reflected between the pond bottom and its surface.

3.2. Inherent optical properties of under-pond ice. The main factor governing the melt pond reflection is its bottom albedo A_b. Scattering in the under-pond ice is mainly caused by air bubbles and brine inclusions [6—7].

The upper layer of sea ice usually contains a significant amount of air bubbles [6, 41], with volume concentration reaching values of 5 % and decreasing with depth. We recall that just the under-pond ice, not the surface scattering layer (white ice), is considered here.

The refractive index of air (relative to ice) in the interval 0.35—0.95 µm changes from 0.755 to 0.768 with average value of 0.763 within this interval. Since air bubbles in ice are optically hard (the refractive index of air differs strongly from that of ice) and do not absorb light, scattering by bubbles of this size range is described by the laws of geometrical optics. The corresponding average cosine of the scattering angle, obtained with the Mie calculations, takes values from 0.851 to 0.865 with the mean value of 0.860, and therefore its spectral variability within the considered spectral range does not exceed 2 %.

Brine inclusions are optically soft, i.e., their refractive index (brine relative to ice) is close to unit. Their sizes are much larger than the wavelength and their shapes are strongly irregular. Their optical characteristics are described within the WKB approximation, applied for irregularly shaped particles [23]: the scattering efficiency $Q_{sca} = 2$, dimensionless optical particle size $x = 1/(n_b - 1)$, scattering phase function and its average cosine are

$$p(\theta) = \frac{2x^2(1+\mu^2)}{\left(1+2x^2(1-\mu)\right)^2}, \qquad \mu = \cos\theta, \qquad 1-g = \frac{\log 2x - 1}{x^2}. \tag{10}$$

Light scattering properties of sea ice are determined by a combination of those of brine inclusions and air bubbles:

$$\sigma = \sigma_b + \sigma_a, \quad \sigma_t = \sigma_b^t + \sigma_a^t,$$
$$p(\theta) = \frac{\sigma_b}{\sigma}p_b(\theta) + \frac{\sigma_a}{\sigma}p_a(\theta), \tag{11}$$
$$1-g = \frac{\sigma_b}{\sigma}(1-g_b) + \frac{\sigma_a}{\sigma}(1-g_a) = \frac{\sigma_t}{\sigma},$$

where $\sigma_t = (1-g)\sigma$ is the transport scattering coefficient and the subscripts a and b refer to air bubbles and brine inclusions, respectively.

3.3. Bottom albedo. If both the absorption and transport scattering coefficients are known, the albedo of a layer can be calculated within the two-stream approximation, which is widely used for practical calculations:

$$A_b = A_0\frac{1-\exp(-2\gamma_i\tau_i)}{1-A_0^2\exp(-2\gamma_i\tau_i)}, \tag{12}$$

where A_0 is the albedo of the semi-infinite layer with the same optical characteristics, γ_i is the asymptotic attenuation coefficient for the under-pond ice and τ_i is its optical thickness. The version of the two-stream approximation developed by [42] expresses these characteristics as follows:

$$A_0 = 1 + t - \sqrt{t\left(t+2\right)}, \quad \gamma_i = \frac{3}{4}\frac{\sigma_t}{\sigma_t+\alpha_i}\sqrt{t\left(t+2\right)}, \qquad \tau_i = (\sigma_t+\alpha_i)H, \qquad t = \frac{8\alpha_i}{3\sigma_t}, \tag{13}$$

where α_i is the absorption coefficient of ice and H is the ice layer thickness.

The two-stream approximation in the version given in [42] has a wide range of applicability and can be used both for strongly and weakly absorbing media, for optically thin and thick layers. Hence, this approximation can be applied to all the variety of melt ponds: from young ponds, which are light blue and have comparatively optically thick under-pond ice, to mature dark ones, where under-pond ice is optically thin.

Thus, the main reflective properties of the melt pond, including their spectral dependence, are determined by only three independent parameters: pond depth z, ice layer thickness H, and transport scattering coefficient of ice σ_t, which does not depend on the wavelength.

3.4. Verification of the melt ponds reflection model. The developed optical model has been verified with data of in situ field measurements performed during three field campaigns on landfast and pack ice in the Arctic (Polarstern-2012, Barrow-2008, and SHEBA-1998). All the comparisons were performed including the atmospheric correction of measured data, which is necessary for data processing of in situ measurements in polar regions [39]. Rayleigh atmosphere with the Arctic Background aerosol [43] was assumed. The measured pond albedo spectra were fitted with the spectra, modeled with eqs. (7)—(13), by varying the pond parameters (z, H, and σ_t). We confine ourselves here to a typical example presented in fig. 3. A reader could find a lot of comparisons of measured and simulated reflection spectra in [25], where it is shown that the model is able to reproduce the albedo spectrum in the visible range with RMSD that does not exceed 1.5 % for a wide variety of melt pond types observed in the Arctic.

4. Conclusion. This paper sums up the studies on inherent optical properties of summer sea ice and reflection of solar light by ice floes in the Arctic that was performed by authors for last few years and published in several works [13, 22—25, 37, 39, 40], where a reader can find all desired details. Below we formulate the main results of this work.

As a result of summer ice melting, some part of an ice floe surface becomes covered by highly scattering top layer, known as “white ice”, while melt ponds occupy the remaining part of the floe [2, 19]. The model of white ice suggested and used in our papers is a random mixture of ice particles and air inclusions [22]. Using the stereological approach the analytical equations for the inherent optical characteristics of white ice (the extinction and absorption coefficients and scattering phase function) are obtained [22, 24]. These optical characteristics are determined by the mean effective grain size, the ice complex refractive index, and by absorption of various possible pollutants. Basing on available field data the presented model currently includes only one pollutant (the seawater yellow substance). However, scattering and/or absorption by any sediment and pollutants can be easily incorporated into the described model. The analytical solutions for the spectral-angular characteristics of the white ice reflectance are developed within the theory of radiative transfer for optically thick layers [24] and successfully verified numerically with the radiative transfer code RAY [36].

The structural formula for melt pond albedo was given by Makshtas and Podgorny [21]. The main factor governing the melt pond reflection is the bottom albedo. Two important developments required for describing

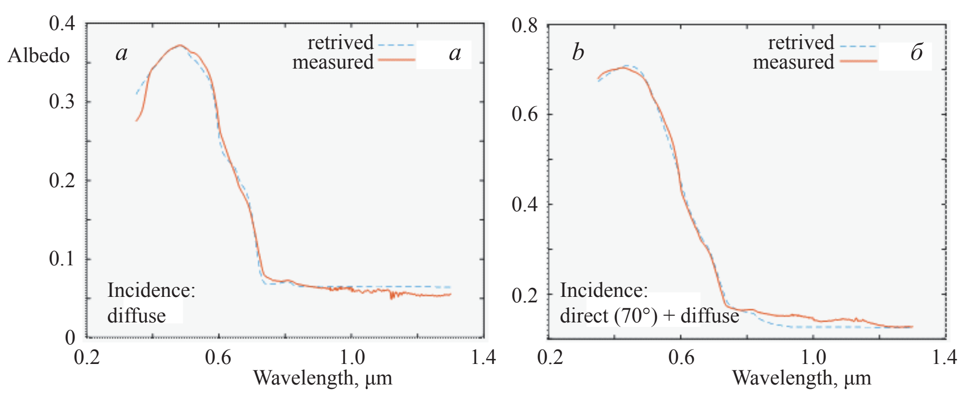

Fig. 3. Typical dark (*a*) and bright blue (*b*) pond spectra, measured during the Polarstern-2012 expedition and simulated with eqs. (7)—(13).

Рис. 3. Типичные спектры тёмной (*a*) и светло-голубой (*б*) снежницы, измеренные в экспедиции Polarstern-2012 и рассчитанные по формулам (7)—(13).

the melt pond reflection were made: the solutions for the melt pond bi-directional reflectance and for albedo of the pond bottom (under-pond ice). The IOPs of the under-pond ice are determined mainly by air bubbles and brine inclusions (for details see [23, 25]).

Finally, it is shown that in the spectral range of 0.3—1.1 μm the reflective properties (including their spectral behavior) of white ice are determined by only three independent parameters: the optical thickness of a scattering layer, effective grain size, and absorption coefficient of the yellow substance at 390 nm. The determining parameters for melt pond reflectance are the pond depth, under-pond ice thickness, and transport scattering coefficient of the under-pond ice. Thereby the optical model of the solar light reflection by summer Arctic ice is developed and presented here.

The verifications with field campaigns in the Arctic (SHEBA-1998, Barrow-2008, and Polarstern-2012) have shown that the models developed for white ice and melt ponds are sufficiently reliable: most of the measured spectra are retrieved with a high degree of accuracy by fitting the abovementioned few parameters. Particularly, it was shown that the model of white ice works satisfactory even in the cases that stand out of the initial frames of the model such as wet ice/snow, crusted snow, frozen cracks, and snow covered ponds.

The results summarized in this paper have got a lot of applications (see, for instance, Section 1). But just requirements of satellite remote sensing of polar regions have been the impetus to the development of the aspects of sea ice optics. The theory briefly overviewed in this paper serves as a base for MPD (Melt Pond Detection) algorithm and code [37]. The MPD has been implemented for bulk data processing at the Institute of Environmental Physics, University of Bremen and the entire historic MERIS dataset 2002–2012 has been processed and analyzed [13]. Currently the new version of the MPD code for processing data of other satellite spectral optical sensors (particularly Sentinel 3) is under development.

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