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# Algorithm to retrieve the melt pond fraction and the spectral albedo of Arctic summer ice from satellite optical data

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## ABSTRACT

A new algorithm to retrieve characteristics (albedo and melt pond fraction) of summer ice in the Arctic from optical satellite data is described. In contrast to other algorithms this algorithm does not use a priori values of the spectral albedo of the sea-ice constituents (such as melt ponds, white ice etc.). Instead, it is based on an analytical solution for the reflection from sea ice surface. The algorithm includes the correction of the sought-for ice and ponds characteristics with the iterative procedure based on the Newton–Raphson method. Also, it accounts for the bi-directional reflection from the ice/snow surface, which is particularly important for Arctic regions where the sun is low. The algorithm includes an original procedure for the atmospheric correction, as well. This algorithm is implemented as computer code called Melt Pond Detector (MPD). The input to the current version of the MPD algorithm is the MERIS Level 1B data, including the radiance coefficients at ten wavelengths and the solar and observation angles (zenith and azimuth). Also, specific parameters describing surface and atmospheric state can be set in a configuration input file. The software output is the map of the melt ponds area fraction and the spectral albedo of sea-ice in HDF5 format. The numerical verification shows that the MPD algorithm provides more accurate results for the light ponds than for the dark ones. The spectral albedo is retrieved with high accuracy for any type of ice and ponds.

## 1. Introduction

Knowledge of properties of the Arctic ice cover is of great importance for modeling and predicting the global climate and for ship navigation in the Arctic Ocean (Serreze et al., 2000; Shindell & Faluvegi, 2009; Untersteiner, 1990). Extensive melting in the summer affects the entire sea-ice structure; particularly, it changes the upper layer of ice, producing the melt ponds on its surface (Perovich et al., 2009; Polashenski, Perovich, & Courville, 2012). Melt ponds change the radiative balance in the Arctic, because they drastically reduce the ice albedo and, therefore, increase the flux of absorbed sun light energy and speed up the melting process (positive feedback mechanism) (Curry, Schramm, & Ebert, 1995). Melt ponds are not just one of the most important factors affecting the ice albedo, but also one of the most variable (Barry, 1996; Eicken, Grenfell, Perovich, Richter-Menge, & Frey, 2004). Ice albedo, in its turn, is among the most crucial parameters, which govern the climate processes in the Arctic (Køltzow, 2007; Pirazzini, 2008). In particular, changes of the ice albedo modulate the strength of the subpolar westerlies and storm tracks (Dethloff et al., 2006). It is also important that with decrease of the ice thickness the ice pack becomes more sensitive to the ice-albedo feedback (Perovich, Richter-Menge, Jones, & Light, 2008; Pistone, Eisenmann, & Ramanathan, 2014; Serreze, Barrett, & Cassano, 2011).

Therefore, the availability of temporally and spatially continuous data on sea-ice albedo and melt pond fraction products is crucial (see, e.g. Schröder, Feltham, Flocco, & Tsamados, 2014). These products can serve as an input for Global Climate Models or be utilized in studies of melt evolution mechanisms (Flocco, Feltham, & Turner, 2010; Flocco, Schroeder, Feltham, & Hunke, 2012; Hunke, Hebert, & Lecomte, 2013; Lüpkes et al., 2013).

The objective of this work is to develop an algorithm to retrieve summer ice albedo and the area fraction of melt ponds on sea ice from data of optical satellite sensors.

The MPD algorithm for retrieval of the ice albedo and melt pond fraction from satellite measurements is based on field measurements of the reflectance spectra of ice and ponds (Istomina, Nicolaus, & Perovich, 2013; Polashenski et al., 2012). Other known algorithms of melt pond fraction retrieval from the optical satellite data (Rösel et al., 2012; Tschudi, Maslanik, & Perovich, 2008) use the a priori fixed spectral reflection coefficients for different pixel constituents, such as snow, bare ice, melt ponds, and open water. However, the physical properties of these constituents, e.g. the ice or snow thickness and the typical grain size, the pond depth, and the albedo of pond bottom, are highly variable,

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and so are their optical properties. This variability can result in substantial errors in pond fraction retrieval. For example, the dark ice may result in overestimation of the melt pond fraction. Conversely, the light pond can be misclassified as unponded ice. At the same time the optical properties (e.g., the reflection coefficients) of ice and ponds have different spectral behavior. So, using a sufficient number of spectral channels, we can set, in principle, the problem not just to retrieve their fractions, but also to estimate some of their characteristics (e.g. the optical thicknesses of ice, the pond depth, the albedo of its bottom etc.). In this work we are making the first attempt to develop an algorithm for pond fraction retrieval from the satellite data without a priori fixed values of the spectral reflection coefficients of the pixel constituents and with simultaneous estimation of ponds and ice properties.

The second feature of the proposed MPD algorithm is that it accounts for bi-directional reflectance of the ice/snow surface. This feature is especially important in the Arctic where the sun is low and the light incidence is oblique (Zege et al., 2011). Particularly, the Fresnel reflection from melt pond surface (glint) at oblique incidence is very high. At the common geometry of measurements, when the observation is not much different from nadir, this glint is not seen from a satellite, but it contributes significantly to the albedo value. It is one more reason why the Lambertian approximation is not suitable for this problem. Moreover, using the albedo instead of the radiance coefficient (bi-directional reflectance distribution function — BRDF) can lead to unrealistic results.

The third specific feature of the MPD algorithm is the procedure of the atmospheric correction of the satellite data, included directly into the iterative retrieval process (see Section 2.3.1).

## 2. Retrieval algorithm

### 2.1. Physical and optical properties of sea ice with melt ponds

The basis of the algorithm is the relationship between physical characteristics of melting ice and measured reflectance properties. Systematic investigations of reflection characteristics of Arctic summer ice have been carried out throughout the 20th century (Doronin, 1970; Grenfell & Maykut, 1977; Light, 2010; Mobley et al., 1998; Nazintsev, 1964; Perovich, 1996). A significant contribution to our knowledge was made in the recent years by the Tara drift (Heygster et al., 2012; Nicolaus et al., 2010) and by the Polarstern cruise ARK-27-3 (Boetius et al., 2013). The seasonal changes of the Multi-Year Ice (MYI) structure and reflection, as well as the melt pond emergence and evolution during Arctic summer, are carefully traced in the paper of Perovich, Grenfell, Light, and Hobbs (2002) on the base of the long-term observations. The following pattern can be picked out from this work.

During May the total albedo does not change significantly, being quite high due to the snow cover. Then in June, over several days rapid decrease of albedo takes place because of extensive snow melting. Melt water is accumulated in depressions on the ice surface, forming melt ponds and leaving the drained surface. The latter is covered by small (several mm) pieces of ice. At first glance this cover may look similar to snow. It is called ‘white ice’ (Perovich, 1996). In contrast to snow, white ice is characterized by the larger typical grain size and physical density (typical microphysical/optical parameters can be found in Light, Eicken, Maykut, and Grenfell (1998)). Ice melting and pond formation result in albedo decrease with strong spatial variability. The melting period lasts usually from mid-June to mid-August. Then, from the end of August to early September the freezing begins and the albedo increases, reaching its winter values after a regular snowfall. The months indicated here were typical for the Beaufort and Chukchi seas at the end of the 20th–the beginning of the 21st centuries (Perovich et al., 2002). Nowadays the melt onset has moved to earlier time (in May) in this region (Markus, Stroeve, & Miller, 2009). For regions located at higher latitudes the melting period starts as late as beginning July and is considerably shorter than at the southern latitudes.

The white ice is the bare ice with a substantial surface scattering layer that provides stable high reflectance. As measurements show (Perovich et al., 2002), the spectral albedo of the white ice is comparatively stable and varies in the range 0.75–0.8 in the blue-green region of the spectrum (at 450–500 nm). Tschudi et al. (2008) write: “The white ice category rose from the observation of bare ice at Barrow that had a white appearance due to the presence of a surface scattering layer. This layer was typically a few centimeters thick and consisted of small fragments of deteriorated ice.”

In fact, the optical parameters of white ice are determined by the following main features: the ice grains have arbitrary shapes and sizes, much greater than the wavelength of the visible light. Thus, the main results of snow optics (Kokhanovsky & Zege, 2004) can also be used to describe the optics of white ice and for remote sensing of sea-ice. Further development of optics of snow and ice has been achieved recently with the use of the model of random mixture (Malinka, 2014).

The reflection properties of a layer are described by the spectral bi-directional reflectance distribution function (BRDF) $R(\theta, \theta_0, \varphi, \lambda)$, where $\theta$ and $\theta_0$ are the zenith angles of the observation and illumination directions, respectively, and $\varphi$ is the azimuth angle between them. Hereafter, we will omit the variables $(\theta, \theta_0, \varphi, \lambda)$ of function $R$ for brevity. The reflection of the white ice as well as the reflection of a snow covered ice floe (Zege et al., 2011) can be described using the asymptotic solution for optically thick weak absorbing scattering media (Kokhanovsky & Zege, 2004). The following solution for the BRDF $R_\infty$ of a semi-infinite weak absorbing layer is described in Zege, Ivanov, and Katsev (1991):

$$R_\infty = R_\infty^0 \exp\left[-4q\gamma g(\theta)g(\theta_0)/R_\infty^0\right], \tag{1}$$

where $R_\infty^0$ is the BRDF of the semi-infinite non-absorbing layer with the same scattering phase function; $g(\theta)$, $q$ and $\gamma$ are equal to:

$$g(\theta) = \frac{3}{7}(1 + 2\cos\theta), \tag{2}$$

$$q = \frac{1}{3(1-\omega_0 g)}, \tag{3}$$

$$\gamma = \sqrt{(1-\omega_0)(1-\omega_0 g)}, \tag{4}$$

where $\omega_0$ is the single scattering albedo (the photon survival probability) and $g$ is the mean cosine of the scattering phase function.

Eq. (1) was used in (Zege et al., 2011) for snow remote sensing (Wiebe, Heygster, Zege, Aoki, & Hori, 2013). But unlike snow cover, when a layer with depth of a few cm is optically very thick, an ice floe is more or less translucent and its optical thickness $\tau_{wi}$ is the main parameter that determines its reflection and transmission. In this case, using the asymptotic solution for optically thick layers (Zege et al., 1991), one can get:

$$R = R_\infty^0 \frac{\sinh\left[\gamma\left(\tau_{wi} + 4q\left[1-g(\theta)g(\theta_0)/R_\infty^0\right]\right)\right]}{\sinh[\gamma(\tau_{wi} + 4q)]}. \tag{5}$$

The values $R_\infty^0$, $\omega_0$, and $g$ (and consequently, $q$ and $\gamma$) are calculated with the use of the model of random mixture (Malinka, 2014), which relates the inherent optical properties of a stochastic medium to the complex refractive index and the effective grain size $a_{eff}$.

In Eqs. (2)–(5) the values $R_\infty^0$, $g$, and $\tau_{wi}$ do not depend practically on wavelength in the considered spectral region. The spectral dependence of reflectance is defined by the single scattering albedo $\omega_0$, determined by the complex refractive index of ice (Warren & Brandt, 2008) and the absorption of possible pollutants. The analysis of field data shows (Istomina, Heygster, et al., 2013) that if one consider ice disposed far from the coastline, the spectral dependence of reflectance is described