Oceanologia (2018) xxx, xxx—xxx

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journal homepage: www.journals.elsevier.com/oceanologia/

ORIGINAL RESEARCH ARTICLE

Partitioning of solar radiation in Arctic sea ice during melt season

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Received 28 December 2017; accepted 22 March 2018

KEYWORDS
Arctic sea ice;
Melt pond;
Radiation transfer;
Mass balance;
Numerical modelling

Summary The partitioning of solar radiation in the Arctic sea ice during the melt season is investigated using a radiative transfer model containing three layers of melt pond, underlying sea ice, and ocean beneath ice. The wavelength distribution of the spectral solar irradiance clearly narrowed with increasing depth into ice, from 350—900 nm at the pond surface to 400—600 nm in the ocean beneath. In contrast, the net spectral irradiance is quite uniform. The absorbed solar energy is sensitive to both pond depth (H_p) and the underlying ice thickness (H_i). The solar energy absorbed by the melt pond (Ψ_p) is proportional only to H_p. However, the solar energy absorbed by the underlying ice (Ψ_i) is more complicated due to the counteracting effects arising from the pond and ice to the energy absorption. In September, Ψ_p decreased by 10% from its August value, which is attributed to more components in the shortwave band (<530 nm) of the incident solar radiation in September relative to August. The absorption coefficient of the sea ice only enhances the absorbed energy in ice, while an increase in the ice scattering coefficient only enhances the absorbed energy in the melt pond, although the resulted changes in Ψ_p and Ψ_i are smaller than that in the albedo and transmittance. The energy absorption rate with depth depends strongly on the incident irradiance and ice scattering, but only weakly on pond depth. Our results are comparable to previous field measurements and numerical simulations. We conclude that the

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Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

https://doi.org/10.1016/j.oceano.2018.03.002

Please cite this article in press as: Lu, P., et al., Partitioning of solar radiation in Arctic sea ice during melt season. Oceanologia (2018), https://doi.org/10.1016/j.oceano.2018.03.002

incident solar energy was largely absorbed by the melt pond rather than by the underlying sea ice.

1. Introduction

A steady decline in Arctic sea ice, especially during the melt seasons since 2000, has been well demonstrated (e.g. Comiso et al., 2017). An increase in solar radiation absorbed by the Arctic Ocean was also observed by satellite instruments during the same period (NASA, 2014). The partitioning of solar radiation in an ice-covered sea is a central issue of the energy budget of the Arctic Ocean and the mass balance of Arctic sea ice (Lei et al., 2016; Wang et al., 2014, 2016). The solar energy absorbed by the sea ice cover largely determines the rate of ice melting (Hudson et al., 2013), while the backscattering part provides heats to the atmosphere (Perovich, 2005). Energy penetrating through the sea ice cover warms up the ocean beneath the ice, which is a primary source of ocean heat (Katlein et al., 2015). The apparent optical properties (AOPs) — albedo (reflectance) and transmittance — determine the partitioning of solar radiation into backscattering, absorption and transmittance in the Arctic sea ice (Perovich, 1996).

Extensive field observations have been carried out to measure the AOPs of first-year (FYI) and multiyear sea ice (MYI), and were employed to parameterize the distribution of solar energy in numerical models (e.g. Taskjelle et al., 2015). In Arctic summer, melt ponds pose notable impacts on the AOPs of sea ice. Not only is the albedo of the melting ice significantly lower than that of dry or snow-covered ice, but melt ponds take more solar radiation which then penetrates the ice (Webster et al., 2015). Even a skim layer of liquid water on an ice surface can change the AOPs considerably (Light et al., 2015). For example, the transmittance through FYI is almost three times larger than through MYI because of the larger melt-pond coverage of FYI, and the energy absorption is also 50% larger in FYI than in MYI (Nicolaus et al., 2012). Ponded ice transmits roughly 4.4 times more total energy into the ocean than nearby bare ice. The ubiquitous surface-scattering layer and drained layer present on bare sea ice are responsible for its relatively high albedo and low transmittance, while light transmittance through ponded ice depends on its physical thickness and the magnitude of the scattering coefficient in the ice interior (Light et al., 2015).

Radiative transfer models (RTM) are another approach to determine the partitioning of solar radiation in melting sea ice. A plane-parallel melt pond model with either a Lambertian or a non-Lambertian reflector for the pond bottom was developed to estimate the pond albedo and radiance distribution in ponded ice (Podgorny and Grenfell, 1996). Solar-radiation flux transfer in melt ponds was simulated by Skyllingstad et al. (2009), and variations in the pond albedo with pond depth and the underlying ice albedo were proposed. Influences of different impact factors on the pond albedo and transmittance were investigated, and a parameterized pond albedo as a function of both pond depth and ice thickness was suggested (Lu et al., 2016). This parameterization is more suitable for thinning Arctic sea ice than the exponential relationship between albedo and pond depth (Morassutti and Ledrew, 1996), which is valid for thicker ice.

A summary of previous field and numerical studies on the AOPs of melting sea ice is listed in Table 1, where α and T denote the percentage of solar energy backscattered by the pond surface and transmitted into the ocean beneath ice, respectively, and Ψ_p and Ψ_i are the fractions absorbed by the melt pond and the underlying ice layer, respectively. Some studies combined the absorption of melt ponds and the underlying ice, and present it as the sum of Ψ_p and Ψ_i.

The results of the studies that considered the partitioning of solar energy in melting sea ice differ widely from each other, as seen in Table 1. One can attribute the variations to the different ice conditions in the studies. As such, a systemic investigation on the various factors that affect the energy distribution is still needed. In addition, the portion of solar energy absorbed by meltwater is obviously larger than that absorbed by underlying sea ice, which argues for the notable capacity of melt ponds in energy absorption, and which also implies the possible complicated processes associated with the allocation of energy to the air, pond, ice, and the water below. However, melt ponds are always treated as a controller of surface albedo, and are not individually considered in numerical models (Pedersen et al., 2009); hence, an investigation of their full physics is required.

To achieve these goals, an RTM initially developed to parameterize melt-pond albedo (Lu et al., 2016) was used. The framework of the RTM is summarized in Section 2. In Section 3 we investigate the distribution of solar radiation, the energy budget in the melting sea ice, and the absorption ratio of solar energy. Discussions on the surface transmission parameter, ice internal melt, and photosynthetically active radiation (PAR) beneath the ice are presented in Section 4. Conclusions are drawn in Section 5.

2. Model description

Radiation transfer in a plane-parallel medium can be simplified as two streams: upwelling and downwelling irradiances. These are governed by two coupled first-order differential equations under the assumptions of diffuse incident solar radiation and isotropic scattering (Flocco et al., 2015):

$$\begin{cases} dF^{\downarrow}(z,\lambda) = -k_\lambda F^{\downarrow}(z,\lambda)dz - \sigma_\lambda F^{\downarrow}(z,\lambda)dz + \sigma_\lambda F^{\uparrow}(z,\lambda)dz \\ dF^{\uparrow}(z,\lambda) = k_\lambda F^{\uparrow}(z,\lambda)dz + \sigma_\lambda F^{\uparrow}(z,\lambda)dz - \sigma_\lambda F^{\downarrow}(z,\lambda)dz \end{cases}, \qquad (1)$$

where σ_λ is the wavelength-dependent scattering coefficient and k_λ is the absorption coefficient, which defines the inherent optical properties (IOP) of the medium. $F^{\uparrow}(z, \lambda)$ and $F^{\downarrow}(z, \lambda)$ are the upwelling and downwelling irradiances,

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