**Estimating underwater light regime under spatially heterogeneous sea ice in the Arctic**

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**Abstract**

The vertical diffuse attenuation coefficient for downward irradiance (Kd) is an apparent optical property commonly used in primary production models to propagate incident solar radiation in the water column. In open water, measuring Kd is relatively straightforward when a vertical profile of Ed measurements is available. In the Arctic, the sea surface is characterized by a complex mosaic composed of ridges, snow, melt ponds and leads. The resulting spatially heterogeneous light field in the first metres of the water column makes the determination of Kd challenging. Irradiance profiles performed beneath a dark patch of ice will be characterized by subsurface light maxima whereas Kd calculated beneath an area of high transmission relative to surrounding areas will show inflated values. The main objective of this work is to propose a new method to estimate an average Kd that is representative of a given large spatially heterogeneous area characterized by drifting phytoplankton. Using both in situ data and 3D Monte Carlo numerical simulations, we show that (1) the large-area average downward irradiance profile (z) under heterogeneous sea ice cover can be represented by a single-term exponential function and (2) the vertical attenuation coefficient for upward radiance (KLu), which is up to two times less influenced by a heterogeneous incident light field than KE in the vicinity of a melt pond, can be used as a proxy to propagate (z) in the water column.

**Keywords:** apparent optical properties, 3D Monte Carlo numerical simulations, downward irradiance, upward radiance, sea ice heterogeneity, vertical attenuation coefficient, melt ponds

**Introduction**

The vertical distribution of underwater light is an important driver of many aquatic processes, such as primary production by phytoplankton, and photochemical reactions, such as the photodegradation of organic matter. Hence, an adequate description of the underwater light regime is mandatory to understand energy fluxes in aquatic ecosystems. In open water, when assuming an optically homogeneous water column, downward irradiance at any given wavelength follows quite well a monotonically exponential decrease with depth, which can be modelled as follows (Kirk 1994):

where Ed(z) is the downward irradiance (W m-2) at depth z (m), Ed(0-) is the downward irradiance (W m-2) just below the surface and Kd(z) is the diffuse vertical attenuation coefficient (m-1) describing the rate at which light decreases with increasing depth. Kd is one of the most commonly used apparent optical properties (AOP) of seawater, and a precise estimation of this parameter is generally essential for measuring or modelling primary production. For example, to determine primary production based on on-deck simulated incubations or photosynthetic parameters derived from photosynthesis vs. irradiance curves (P vs. E curves) requires measured or estimated values of Kd (e.g. Morel 1996). Nowadays, Kd is relatively easy to estimate using commercially available radiometers.

In the Arctic, a complex mosaic composed of ice, snow, leads, melt ponds and open water characterizes the surface of ice-infested waters (Nicolaus 2013, Katlein 2015, Katlein 2016, Oziel 2018). There, phytoplankton is exposed to a highly variable light regime while drifting under these features (e.g. Lange 2017). Estimating primary production of phytoplankton under sea ice requires an approach that is adequate to capture this large-area variability in the light field. In situ incubations at single locations of seawater samples inoculated with 14C or 13C are not appropriate because they reflect primary production under local light conditions, which is not representative of the range of irradiance experienced by drifting phytoplankton over a large area. One classical approach that is more adequate consists in conducting on-deck simulated 24-hour incubations of seawater samples inoculated with 14C or 13C and applying the average light attenuation at the depths of sample collections, using natural illumination and neutral filters. An alternative approach consists in calculating primary production using modelled or measured daily time series of incident irradiance, sea ice transmittance and in-water vertical attenuation coefficients, combined with photosynthetic parameters determined on P vs. E curves measured with short (under two hours) incubations of seawater samples inoculated with 14C. Both approaches require that the vertical profile of the irradiance experienced by drifting phytoplankton be appropriately determined, which is challenging due to surface heterogeneity. Traditionally, one or very few Ed(z) profiles are measured at discrete locations under sea ice e.g. (Mundy 2009). Such measurements, however, do not capture the variability induced by sea ice features. In recent studies, to better document the spatial variability of Ed(z), radiometers were attached to either remotely operated vehicles (ROV) (Katlein 2015) or a Surface and Under-Ice Trawl (SUIT), a net developed for deployment in ice-covered waters, typically behind an icebreaker (Lange 2017). Both an ROV and a SUIT allow a better description of the light field right under sea ice, which is more appropriate for determining average irradiance experienced by drifting phytoplankton. Such under-ice measurements can then be combined with averaged Kd values to propagate light at depth.

Propagating Ed(z) using Kd values estimated from a few discrete vertical profiles of Ed(z) under sea ice is a limitation that applies to any strategy for radiometer deployment. Indeed, as the depth of an upward-looking detector increases, light from a larger area on the underside of the ice enters the detector’s field of view and local Ed(z) may not follow the usual monotonically exponential decrease with increasing depth (Equation 1). For example, irradiance profiles performed beneath low-transmission sea ice (e.g. white ice) relative to surrounding areas showing melt ponds, for instance, will show subsurface light maxima. The literature reports subsurface maxima varying between five and 20 metres in depth (Frey 2011, Katlein 2016, Laney 2017). Conversely, it is also important to note that Kd estimations are biased when profiles are performed beneath an area of high transmission (e.g. a melt pond) relative to surrounding areas (Katlein 2016). Indeed, with depth, light decreases more quickly than what would be justified by the inherent optical properties of the water column. In the field, this situation is more difficult to identify compared to profiles showing subsurface maxima because the former measurements may appear to follow a single exponential decrease but would not produce a diffuse attenuation coefficient that adequately describes the water mass. Consequently, two vertical light profiles measured a few metres apart under sea ice are often very different. Hence, local measurements of light under heterogeneous sea ice do not provide an adequate description of the average light field as it would be seen by drifting phytoplankton cells at different depths. This makes estimations of primary production and the interpretation of biogeochemical data challenging in the presence of sea ice.

To fit vertical profiles of Ed(z) that do not follow an exponential decay under sea ice covered with melt ponds, Frey (2011) proposes a simple geometric model (Equation 2).

where Ed(0-) is the irradiance directly below the ice/snow, P the areal fraction of the ice cover, N the ratio between ice and melt ponds transmittance and ɸ a fitting parameter defined as arctan(R/z) with R the radius of the ice patch. A major drawback of this method is that additional field observations of N and P are required to adequately parameterize the model, which makes its use more difficult. To address this concern, Laney (2017) proposed a semi-empirical parameterization that includes a second exponential coefficient in Equation 1 to model light decrease at the interface between the ice and ocean water at the bottom of the ice layer:

where Ed(0-) is the irradiance that would be observed under homogeneous snow or ice cover, Ed(NS) is the irradiance under ice, and KNS describes the decrease of Ed(0-) just under the ice layer. Both the methods by Frey (2011) and Laney (2017) make it possible to propagate local Ed(z) vertically under specific sea ice features but do not make it possible to identify and correct for inflated Kd when profiles are performed beneath an area of high transmission relative to surrounding areas. Additionally, when trying to determine primary production by phytoplankton that drift under sea ice and therefore are not static under sea ice features, what matters is the average shape of the vertical Ed(z) profile, which may possibly be predictable using a large-area Kd as under a wavy open ocean surface (Zaneveld 2001).

In this study, using both in situ data and 3D Monte Carlo numerical simulations of radiative transfer, we show that the vertical propagation of average Ed(z), (z), is reasonably well approximated by a single exponential decay with a so-called large area under sea ice covered in melt ponds. We further demonstrate that the large area can be estimated from measurements of the vertical attenuation coefficient for upward radiance (KLu) because the latter is believably less affected by local surface features of the ice cover.

**Material and methods**

**Study site and field campaign**

The field campaign was part of the GreenEdge project (www.greenedgeproject.info) which was conducted on landfast ice southeast of the Qikiqtarjuaq Island in Baffin Bay (67.4797N, −63.7895W). The field operations took place at an ice camp where the water depth was 360 m, from April 20 to July 27, 2016 (Supplementary Fig. 1). During the sampling period, the study site experienced changes in the snow cover and landfast ice thickness of between 0-49 and 106-149 cm, respectively.

**In situ underwater light measurements**

During the campaign, a total of 83 vertical light profiles were acquired using a factory-calibrated ICE-Pro (an ice floe version of the C-OPS, or Compact-Optical Profiling System, from Biospherical Instruments Inc.) equipped with both downward plane irradiance Ed (W cm-2) and upward radiance Lu (W cm-2 sr-1) radiometers . The ICE-Pro system is a negatively buoyant instrument with a cylindrical shape 10 inches in diameter, and is not designed for free-fall casts (as opposed to its open-water version). To perform the triplicate profiles, the frame was manually lowered into an auger hole that had been cleaned of ice chunks. Once it was underneath the ice layer, fresh clean snow was shovelled back in the hole to prevent the creation of a bright spot right on top of the sensors. Great care was taken not to pollute the hole surroundings (footsteps, water and slush spillage from the auger drilling, etc.). The operator then stepped back 50 m, while keeping the sensors right under the ice, to avoid any human shadow on top of the profile. The frame was then lowered manually at a constant descent rate of approximately 0.3 m s-1. The above-surface atmospheric reference sensor was fixed on a steady tripod standing on the floe approximately 2 m above the surface and above all neighbouring ice camp features. Data processing and validation were performed using a protocol inspired by the one proposed by Smith (1984), which is now used by the main space agencies. Measurements were made at 19 wavelengths: 380, 395, 412, 443, 465, 490, 510, 532, 555, 560, 589, 625, 665, 683, 694, 710, 765, 780 and 875 nm. For this study, Ed and Lu spectra were interpolated linearly between 400 and 700 nm every 10 nm. In situ diffuse attenuation coefficients (K) for both Ed (Kd) and Lu (KLu) were calculated on a 5-m sliding window (10-15 m, 15-20 m, …, 70-75 m, 75-80 m) starting at 10 m to reduce the effects of surface heterogeneity. A total of 72,044 non-linear models were calculated to estimate both K coefficients from Equation 1 (83 profiles × 14 depths × 31 wavelengths × 2 radiometric quantities (Ed, Lu)). A conservative R2 of 0.99 was used to filter out poor models (i.e. noisy profiles that did not follow a local exponential decrease). 42,407 models were kept for subsequent analysis.

**3D Monte Carlo numerical simulations**

**Theory and geometry**

3D numerical Monte Carlo simulation is a convenient approach for modelling the light field under spatially heterogeneous sea surfaces (Mobley\_ocean\_optics\_book, Petrich 2012, Katlein 2014, Katlein 2016). They are simple to understand and versatile, and incident light, inherent optical properties (IOPs) and geometry can be easily changed. In this study, we used SimulO, a 3D Monte Carlo software program that simulates the propagation of light in optical instruments or in ocean waters (Leymarie 2010). Our objective was to simulate the propagation of sunlight underneath heterogeneous ice-covered ocean waters. Simulations were performed in an idealized ocean described by a cylinder of 120 m radius and 150 m depth (Fig. 1). The water IOPs were selected to reflect pre-bloom conditions in the green/blue spectral region (a = b = 0.05 m-1). These typical averaged values were measured during the GreenEdge 2016 campaign using an in situ spectrophotometer (ac-s from Sea-Bird Scientific) and represent the contribution of both pure water and the water’s constituents. The scattering phase function was described by a Fournier-Forand analytic form with a 3% backscatter fraction (Fournier 1994, Mobley 2002). The inclusion of a 3D sea ice layer at the upper boundary of the ocean would require extensive computing power because of the high scattering properties of sea ice. Instead, sea ice was incorporated at the upper boundary of the ocean using a 2D light-emitting surface with a radius of 100 m. The angular and amplitude distribution of the light field emitted by the surface was chosen to mimic observed field data (Girard 2018). SimulO does not allow the use of arbitrary angular distribution for photon-emitting surfaces. To overcome this problem, two Lambertian sources of 90 and 60 degrees were summed up in order to reproduce an observed under-ice light field (Fig. 2). The first source was a regular Lambertian emitting surface while the second was a Lambertian emitting surface but restricted to an emission within 60 degrees of the zenith angle. A 5-m-radius melt pond was set up at the centre of the emitting surface (Fig. 1). The melt pond had the same emitting angular distribution as the surrounding ice. Its intensity was four times higher than the surrounding ice, which corresponds to typical conditions found in the Arctic during summer (Perovich 2016).

Given our interest in surface light profiles, 2D horizontal software detectors were placed vertically every 0.5 m, up to a depth of 25 m. Detectors include 1-m2 pixels measuring downward irradiance and upward radiance (5-degree half angle). In order to avoid the effect of the boundary (i.e. absorption by the side of the cylinder used to simulate the water column), data outside a radius of 50 m were not used (see the green box in Fig. 1). A total number of 7.14 × 1010 photons were simulated to obtain a sufficient number of upwelling photons. The simulation took approximately 6,000 hours distributed over 2,000 CPU cores. Since the geometry was symmetrical azimuthally, irradiance and radiance were averaged over the azimuth in order to raise the signal-to-noise ratio. Due to the low scattering coefficients used to reproduce in situ conditions observed during the sampling campaign, radiance profiles were noisy because only a small number of upward photons could be captured. To address this issue, radiance profiles were smoothed using a Gaussian fit (Supplementary Fig. 2).

**Estimation of reference and local light profiles**

To explore how the melt pond influences the averaged underwater irradiance and radiance profiles (Fig. 1), data from the Monte Carlo simulation were averaged according to six different radii, corresponding to varying melt pond proportions. For each case, the simulated light profiles were averaged within the following surface areas: (1) 10-m radius (25% melt pond cover), (2) 11.18-m radius (20% melt pond cover), (3) 12.91-m radius (15% melt pond cover), (4) 15.811-m radius (10% melt pond cover), (5) 22.361-m radius (5% melt pond cover) and (6) 50-m radius (1% melt pond cover). For each of these six configurations, the corresponding averaged light profile, was subsequently viewed as an adequate description of the average underwater light field. For the remainder of the text, these averaged profiles are referred to as reference light profiles. Furthermore, 50 light profiles, evenly spaced by 1 m from the melt pond centre, were extracted to mimic local measurements of light and to calculate associated diffuse attenuation coefficients.

**Statistical analysis**

All statistical analyses and graphics were carried out with R 3.5.1 (RCoreTeam 2018).

**Results**

**Comparing in situ downward irradiance (Ed) and upward radiance (Lu) measurements**

An example showing in situ downward irradiance (Ed) profiles and upward radiance (Lu) profiles at 16 visible wavelengths measured under ice is presented in Fig. 3. For the Ed profiles, subsurface light maxima at a depth of around 10 m are clearly visible between 400 and 560 nm. These peaks are not visible in the yellow/red region (580-700 nm). For the Lu profiles, no subsurface light maxima were found at any wavelength. In a closer look at the shape of both Ed and Lu light profiles, data below 10 m were normalized to the value at 10 m (Fig. 4). Below 10 m and between 400 and 580 nm, both Ed and Lu profiles presented the same shape (i.e. yield the same rate of extinction with increasing depth). At longer wavelengths (≥ 600 nm), differences between the shapes of Ed and Lu profiles increased. Irradiance and radiance-diffuse attenuation coefficients (Kd and KLu) calculated on layers of a 5-m depth are compared in Fig. 5 for all 83 profiles. In the blue/green/yellow regions (400-580 nm), the determination coefficients between KLu and Kd varied between 0.98 at the surface (10-15 m) and 0.64 at depth (75-80 m). For most of the surface layer, regression lines lined up with the 1:1 lines. Slight deviations from the 1:1 lines started to appear after 60 m where Kd was on average higher than KLu. Relationships including orange and red wavelengths are presented in Supplementary Fig. 3. A linear regression analysis between all in situ normalized Ed and Lu profiles showed that determination coefficients (R2) range between 0.75 and 1 (Supplementary Fig. 4). A sharp decrease and a high variability of calculated R2 occurred beyond 575 nm. This suggests a gradual decoupling between Ed and Lu profiles at longer wavelengths, likely due to the effect of inelastic scattering (mostly, Raman). To validate this hypothesis, we used the HydroLight radiative transfer numerical model to calculate downward irradiance and upward radiance and their associated attenuation coefficients in a water column. Two simulations, with and without Raman scattering, were carried out. The simulations were parameterized using IOPs measured during the field campaign (detailed information can be found in the supplementary section entitled *Raman inelastic scattering*). The HydroLight simulations showed the same decoupling between Kd and KLu around 600 nm (Supplementary Fig. 5) as we observed with the in situ data (Fig. 4-5, Supplementary Fig. 3-4). Furthermore, the consequences of this decoupling are limited, as we observed no significant differences between photosynthetically active radiation (PAR) calculated using irradiance profiles modelled with or without Raman scattering (Supplementary Fig. 6).

**3D Monte Carlo numerical simulations**

Fig. 6 shows the map of the simulated downward irradiance and upward radiance. A key difference for the upcoming discussion is that the simulated upward radiance was more homogeneous compared to the simulated downward irradiance. Fig. 7 shows the reference irradiance, ((z)), and reference radiance, (), profiles. The highest irradiance and radiance occurred when the melt pond occupied 25% of the sampling area, allowing for more light to propagate in the water column. None of the and reference profiles showed subsurface light maxima. Fig. 8 shows the 50 simulated local downward irradiance and upward radiance light profiles evenly spaced by 1 m from the melt pond centre. Local downward irradiance profiles under the melt pond (0-5 m) showed a rapid decrease with increasing depth described by a monotonically exponential or quasi-exponential decrease. Local simulated downward irradiance profiles just outside the melt pond (5-10 m) were characterized with subsurface light maxima occurring at a depth of between approximately 5 and 10 m. Further away from the melt pond centre, downward irradiance profiles followed a monotonically exponential or quasi-exponential decrease. None of the simulated upward radiance light profiles presented subsurface light maxima (Fig. 8). From local simulated irradiance and radiance profiles (Fig. 8), Kd and KLu were calculated by fitting Equation 1 between 0 and 25 m. Results are presented in Fig. 9. Kd varied between 0.065 and 0.157 m-1 and KLu between 0.079 and 0.116 m-1. Then, these Kd and KLu were used in combination with surface reference values d(0-). Fig. 10 shows the profiles resulting from this operation. A greater dispersion around the reference profiles (thick black lines in Fig. 10) occurred when using Kd compared to the profiles generated with similarly derived KLu values. The relative differences between the depth-integrated values of each local profiles (coloured lines in Fig. 10) and the depth-integrated values of the reference profiles (thick black lines in Fig. 10) were used to quantify the error of using either Kd or KLu as a proxy to predict downward irradiance in the water column (Fig. 11). Below the melt pond, Kd overestimated total downward irradiance by up to 40%. In this region, the local Ks are inflated. In the transition region, between 5 and 10 m from the centre of the melt pond, where subsurface maxima are observed, Kd underestimate the downward irradiance by up to 35%. Further away from the edge of the melt pond, the errors saturated to maximum -25%.

The mean relative errors were lower by approximately a factor of two when using KLu (-7%) compared to Kd (-12%). The prediction errors stabilized at a shorter distance from the centre of the melt pond when using KLu (~10 m) compared with using Kd (~20 m). Furthermore, the largest error occurred when the melt pond occupied 25% of the area (Fig. 1) used to derive the reference average profile (Fig. 10).

**Discussion**

In the Arctic, melt pond coverage, lead coverage, and ice and snow thickness can vary greatly in both time and space (Landy 2014, Eicken 2004). Due to this sea ice heterogeneity, local under-ice measurements of downward irradiance are sometimes characterized by subsurface light maxima (Fig. 3). To model such profiles, Laney (2017) proposed a semi-empirical parameterization using two exponential terms (see Equation 3). Whereas their method might provide adequate estimations of instantaneous downward diffuse attenuation coefficients at specific locations, fitting a double exponential might not be ideal because data are modelled locally and do not provide an adequate description of the average light field () as it would be seen, for example, by drifting phytoplankton cells. In such conditions, this paper argues that under ice irradiance measurements should be analyzed in the context of ice and surface properties within a radius of several metres over the horizontal distance since local measurements do not reproduce the full variability of the under-ice light field (Katlein 2015).

Using in situ light measurements, it was found that Ed and Lu (and therefore Kd and KLu) were highly correlated below 10 m depth (Fig. 4, Fig. 5), even when subsurface light maxima were present (Fig. 3). One possible explanation is that a Lu radiometer measures scattered light originating from a larger surface area, which reduces the effect of sea ice heterogeneity. Accordingly, no subsurface light maxima were observed in the in situ upward radiance profiles. This reinforces the idea that Lu is less influenced by sea ice surface heterogeneity.

Based on Monte Carlo simulations, our results showed that the average downward irradiance profile, (z), under heterogeneous sea ice cover follows a single-term exponential function, even when melt ponds occupy a large fraction of the study area (Fig. 7). This is similar to what is observed under a wavy ice-free surface (Zaneveld 2001). However, estimating (z) for a given area is not straightforward, as it requires a large number of local profiles under the sea ice. An intuitive alternative to deriving the attenuation coefficient is to use upward radiance, which is less influenced by sea surface heterogeneity compared to downward irradiance (Fig. 3, Fig. 4, Fig. 5). Monte Carlo simulations showed that a local estimation of KLu could be a better proxy for . Accordingly, simulations showed that using KLu rather than Kd provided better estimations of the average downward profile by reducing the average error by approximately a factor of two (Fig. 11).

There are at least two main factors influencing the quality of in situ downward measurements under heterogeneous sea ice. The first factor is the horizontal distance from the centre of the melt pond. Although the relative error of propagating Ed(0-) using both Kd and KLu showed the same pattern, the largest error occurred when using local estimations of Kd made at a horizontal distance between 1 and 10 m from the melt pond (Fig. 11). In contrast, in the vicinity of the melt pond, the relative error associated with the use of KLu was much lower and stabilized just after approximately 10 m from the centre of the melt pond. The second factor driving the relative error of local measurements is the proportion occupied by melt ponds over the area of interest (Fig. 11). Indeed, higher proportions of melt pond allow for more light to penetrate in the water column. Hence, local measurements made under surrounding ice are more likely to show subsurface light maxima (see Frey 2011). Accordingly, when melt ponds accounted for 1% of the total area, averaged error in Ed(z) using KLu was 1.33% but increased to 18% when the melt pond occupied 25% of the total area (Fig. 11).

**Conclusions**

Our results show that under spatially heterogeneous sea ice at the surface (and for a homogeneous water column), the average irradiance profile, (z), is well reproduced by a single exponential function. We also showed that propagating Ed(0-) using KLu is a better choice compared to Kd under heterogeneous sea ice. Nowadays, radiance measurements are becoming more routinely performed during field campaigns, so we argue that one should use KLu when available to propagate Ed(0-) through the water column under sea ice. The main difficulty remains finding good estimates of averaged Ed(0-). In recent years, this has become easier with the development of remotely operated vehicles (Katlein 2015, Arndt 2017, Nicolaus 2013), remote sensing techniques and drone imagery. In this study, we used a Monte Carlo approach to model an idealized surface with a single melt pond (Fig. 1, Fig. 6). Fig. 10 shows that the effect of a 5-m melt pond disappears at approximately 20 m, suggesting that our results are valid for a given surface where multiple melt ponds would be separated by a distance of approximately 40 m. However, given that in the Arctic, the landscape is characterized by a complex mosaic composed of ice, snow, leads, melt ponds and open water, further work using 3D radiative transfer models is needed to fully understand underwater light distribution below a spatially heterogeneous surface.

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