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

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Journal: <http://www.mdpi.com/journal/applsci/special_issues/ocean_optics>

**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 induced by these features in the first meters of the water column makes the determination of Kd challenging.

For instance, irradiance profiles performed beneath a dark patch of ice will be characterized with subsurface light maxima between ~5-20 m depth 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. 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 an 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 like 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 (Kirk1994):

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 used apparent optical properties (AOP) of seawater and a precise estimation of this parameter is generally essential to measure or model 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. Morel1996). 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 is characterizing the surface of ice-infested waters (Nicolaus2013, Katlein2015, Katlein2016, Oziel2018). There, phytoplankton is exposed to a highly variable light regime while drifting under these features (e.g. Lange2017). Estimating primary production of phytoplankton under sea-ice requires an adequate approach that captures 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, 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 24h incubations of seawater samples inoculated with 14C or 13C and applying the average light attenuation at the depths of sample collection, 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 (< 2h) 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. (Mundy2009). 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) (Katlein2015) or a SUIT (Surface and Under-Ice Trawl), a net developed for deployment in ice-covered waters, typically behind an icebreaker (Lange2017). Both a ROV and the 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 Kd values to propagate light at depth.

Propagating Ed(z) using Kd values estimated from few discrete vertical profiles of Ed(z) under sea-ice is a limitation that applies to any strategy for radiometer deployment, and is, however, very challenging because of surface heterogeneity. Indeed, as the depth of a detector is increased, light from a larger area on the underside of the ice enters the detector’s field of view and e.g. local *Ed(z)* may not follow the usual monotonically exponential decrease with increasing depth (Equation (1)). For example, irradiance profiles performed beneath a low transmission sea ice (e.g. white ice) relative to surrounding areas showing e.g. melt ponds will show subsurface light maxima. Literature reports subsurface maxima varying between ~5-20 m depth (Frey2011, Katlein2016, Laney2017). Oppositely, it is also important to note that Kd are biased when profiles are performed beneath an area of high transmission (e.g. a melt pond) relative to surrounding areas [Katlein2016]. Indeed, light decreases with depth more quickly than would be warranted by the optical properties of the water column. In the field, this situation is more difficult to identify compared to profiles showing subsurface maxima because measurements made under these conditions may appear to follow a single exponential decrease but would still not produce an diffuse attenuation coefficient that not adequately describes the water mass.

Consequently, two vertical light profiles measured a few meters apart under sea ice are often very different. Hence, local measurements of light under heterogeneous sea ice do not allow 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, Frey2011 proposed 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. An important 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, Laney2017 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 ice layer.

where Ed(0-) is the irradiance that would be observed under homogeneous snow/ice cover, Ed(NS) is the irradiance under ice, KNS describes the decrease of Ed(0-) just under the ice layer. Both methods by Frey et al. (2011) and Laney et al. (2017) allow propagating local Ed(z) vertically under specific sea ice features butdo not allow to identify and correct for inflated Kd when profiles are performed beneath an area of high transmission relative to surrounding areas. Additionally,

what matters when trying to determine primary production by phytoplankton that drift under sea ice and, therefore, is not static under sea ice features, 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 et al. 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 with 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 the 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 until July 27 of 2016 (Supplementary Fig. 1). During the sampling period, the study site experienced changes in the snow cover and lanfast ice thickness between 0.32-49.00 and 105.75-149.31 cm, respectively).

**In-situ underwater light measurements**

A total of 83 vertical light profiles using a factory calibrated ICE-Pro (an ice floe version of the C-OPS - 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 were measured during the campaign. The IcePRO system is a negatively buoyant instrument with 10 inches in diameter cylindrical shape and is not designed for free-fall casts (as opposed to its open water version). To perform the triplicate profiles, the frame is manually lowered in an auger hole that has been cleaned for ice chunks. Once underneath the ice layer, clean and fresh snow was shovelled back in the hole to prevent any bright spot right on top of the sensors. A great care was taken not to pollute the hole surroundings (footsteps, water and slush spillage from the auger drilling, etc.). The operator then steps 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 tripod standing on the floe (very steady), approximately 2 m above the surface and above any neighbour ice camp feature. Data processing and validation were performed using a protocol inspired by the one proposed by Smith1984 which is now used by various 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 K 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 were not following 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 to model the light field under spatially heterogeneous sea surface (Mobley\_ocean\_optics\_book, Petrich2012, Katlein2014, Katlein2016). They are simple to understand, 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 that simulates the propagation of light in e.g. optical instruments or in oceanic waters (Leymarie2010). 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 in the during the GreenEdge 2016 campaign using an in-situ spectrophotometer (ACS, *Sea-Bird Scientific*) and represent the contribution of both pure water and water’s constituents (data not published yet). The scattering phase function was described by a Fournier-Forand analytic form with a 3% backscatter fraction (Fournier1994, Mobley2002). 2D light-emitting surfacethe Lambertian to mimic radiance field observed under iceam

Our objective was to simulate the propagation of sunlight inside ice-covered oceanic water. Inclusion of a 3D sea ice layer at the upper boundary of the ocean would required extensive computer 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 of 100 m radius. The angular and amplitude distribution of the light field emitted by the surface was chosen to mimic observed field data (Girard2018). SimulO does not allow to use arbitrary angular distribution for photons emitting surface. To overcome this problem, two Lambertian sources of 90 and 60 degrees were summed up in order to reproduce observed under ice light field (Fig. 2). The first source is a regular Lambertian emitting surface while the second is a Lambertian emitting surface but restricted to an emission within 60 degrees of zenith angle. A 5 m radius melt pond was set-up at the center of the emitting surface (Fig. 1). The melt pond has the same emitting angular distribution as surrounding ice. Its intensity is four times higher compared to the surrounding ice which corresponds to typical conditions found in the Arctic during summer (Perovich2016). For the purpose of this study, the small difference between the light field shape measured under melt pond vs ice is much less important compared the their difference of intensity (Girard2018).

Given our interest in surface light profiles, 2D horizontal software detectors were placed vertically every 0.5 m, up to 25 m depth. Detectors include 1-m2 pixels measuring downward irradiance and upward radiance (5 degrees 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 meters were not used (see the green box in Fig. 1). A total number of 7.14×1010 photons were simulated in order to obtain sufficient number of upwelling photons. Since the geometry is symmetrical azithmutally, irradiance and radiance were averaged over the azithmuth 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 out using Gaussian fit (supplementary Fig. 2). The simulation took approximately 6000 hours distributed over 2000 CPU cores.

**Estimation of reference light profiles**

Data from the Monte-Carlo simulation were averaged according to six different radii, corresponding to varying melt pond proportions, to explore how melt pond influences the averaged underwater irradiance and radiance profiles (Fig. 1). For each case, 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 configurations, averaged light profile, was subsequently viewed as an adequate description of the average underwater light field. For the reminder of the text, these averaged profiles are referred to as reference light profiles. A total of 50 light profiles evenly spaced by one m around the melt pond were further extracted to mimic local measurements of light and to calculate associated diffuse attenuation coefficients (coloured circles in Fig. 1).

**Statistical analysis**

All statistical analysis and graphics were carried out with R 3.5.1 (RCoreTeam2018).

**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 around 10 m depth 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. To look closer at the shape of both Ed and Lu light profiles, data below 10 m have been 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 increase. 2longer).

Irradiance and radiance diffuse attenuation coefficients (Kd and KLu) calculated on five m depth layers 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 shows 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’s scattering were carried out. The simulations were parameterized using IOPs measured during the field campaign (see 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, Fig. 5). We further observed no significant differences between photosynthetically active radiation (PAR) calculated using irradiance profiles modeled with or without Raman’s scattering (Supplementary Fig. 6).

**3D Monte-Carlo numerical simulations**

Fig. 6 shows the map (cross-section?) of the simulated downward irradiance and upward radiance. . The key difference is that simulated radiance was more homogeneous compared to irradiance. . Fig. 7 shows the averaged irradiance, ((z)), and radiance, (), profiles, which are referred to as reference profiles. , showed the same pattern7The highest density of photons occurred when the melt pond occupied 25% of the sampling area, allowing for more light to propagate in the water column. Note that none of the and reference profiles showed subsurface light maxima (Fig. 7).

Fig. 8 shows ….Irradiance

3 zones. 3 phrases

Radiance

3 zones: 1 phrase

Some irradiance profiles modelled outside the melt pond at distances between 5 and 15 m of the center showed the same subsurface light maxima (Fig. 8) as observed on *in situ* profiles (Fig. 3). Beyond approximately 15 m depth, subsurface light maxima disappeared and irradiance profiles followed a monotonically exponential or quasi-exponential decrease (Equation (1)). no were present in the simulated wasFrom both irradiance and radiance profiles, simulated Kd varied between 0.065 and 0.157 m-1 and simulated KLu between 0.079 and 0.116 m-1 (Fig. 8, Supplementary Fig. 7).

Propagating surface reference light (Ed(0-), surface values of the coloured lines in Fig. 7) through the water column using Kd resulted in a greater variability (i.e. the lines on the left columns are more distantly separated from each other compared to those in the right column) compared to the profiles generated with KLu (Fig. 9). The relative differences between both depth-integrated (i.e. total number of photons) reference profiles and predicted profiles were used to quantify the error of using either Kd or KLu as a proxy to predict downward irradiance in the water column (Fig. 10). Overall, the greatest errors in predictions reached approximately 40% when using Kd in the center of the medge melt pond. The mean relative errors were lower by a factor of two when using KLu (-12%) compared to Kd (-7%). The errors of the predictions stabilized at a shorter distance from the center of the melt pond edge 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/snow thickness can vary highly in both time and space (Landy2014, Eicken2004). Due to this sea ice heterogeneity, local under-ice measurements of downward irradiance are often characterized by subsurface light maxima (Fig. 3). To model such profiles, Laney2017 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 is 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, it was argued that under ice, irradiance measurements should be analyzed in the context of ice and surface properties within a radius of several meters over the horizontal distance since local measurements do not reproduce the full variability of the under-ice light field (Katlein2015).

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 (Zaneveld2001). 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 derive 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 good proxy for . Accordingly, simulations showed that under sea ice the propagation of average irradiance (Ed(0-)) using KLu rather than Kd provided better estimations of the average downward profile by reducing the average error by a factor of two (Fig. 9, Fig. 10).

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 center of the melt pondedge. 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 pondm (Fig. 10). In contrast, in the vicinity of the melt pond, the relative errors associated with the use of KLu was much lower and stabilized just after approximately 10 m from the center 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. 10). 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 Frey2011). Accordingly, when melt ponds accounted for 1% of the total area, averaged errors in Ed(z) using KLu was 1.33% but increased to 18% when the melt pond occupied 25% of the total area (Fig. 10).

**Conclusions**

Our results show that under spatially heterogeneous sea ice at the surface, 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. The main difficulty remains at finding good estimates of Ed(0-). In recent years, this became easier with the development of remotely operated vehicles (Katlein2015, Arndt2017, Nicolaus2013), 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). In Fig. 10, one can see that the effect of the 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, a complex mosaic composed of ice, snow, leads, melt ponds and open water is characterizing the landscape, further work using 3D radiative transfer models is needed to fully understand underwater light distribution below spatially heterogeneous ice/snow/pond/open-water surfaces.

**Acknowledgments**

The GreenEdge project is funded by the following French and Canadian programs and agencies: ANR (Contract #111112), CNES (project #131425), IPEV (project #1164), CSA, Fondation Total, ArcticNet, LEFE and the French Arctic Initiative (GreenEdge project). This project would not have been possible without the support of the Hamlet of Qikiqtarjuaq and the members of the community as well as the Inuksuit School and its Principal Jacqueline Arsenault. The project is conducted under the scientific coordination of the Canada Excellence Research Chair on Remote sensing of Canada’s new Arctic frontier and the CNRS & Université Laval Takuvik Joint International laboratory (UMI3376). The field campaign was successful thanks to the contribution of J. Ferland, G. Bécu, C. Marec, J. Lagunas, F. Bruyant, J. Larivière, E. Rehm, S. Lambert-Girard, C. Aubry, C. Lalande, A. LeBaron, C. Marty, J. Sansoulet, D. Christiansen-Stowe, A. Wells, M. Benoît-Gagné, E. Devred and M.-H. Forget from the Takuvik laboratory, C.J. Mundy and V. Galindo from University of Manitoba as well as F. Pinczon du Sel and E. Brossier from Vagabond. We also thank Michel Gosselin, Québec-Océan, the CCGS Amundsen and the Polar Continental Shelf Program for their in-kind contribution in polar logistic and scientific equipment. This research was enabled in part by support provided by Calcul Québec (www.calculquebec.ca) and Compute Canada (www.computecanada.ca). S. L. Girard was supported by a postdoctoral fellowship from The Natural Sciences and Engineering Research Council of Canada (NSERC). We also acknowledge the Canada First Research Excellence Fund, the Sentinel North Strategy for their financial support.