Evaluation of satellite-based algorithms to estimate photosynthetically available radiation (PAR) reaching the ocean surface at high northern latitudes

Julien Laliberté, Simon Bélanger, Robert Frouin

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A B S T R A C T

Two satellite-based methods to estimate daily averaged photosynthetically available radiation (PAR) at the ocean surface are evaluated at high northern latitudes. The first method employs a precomputed Look-Up-Table (LUT) generated from radiative transfer simulations. The LUT associates spectral irradiance reaching the surface to a given set of input parameters, namely solar zenith angle, cloud optical thickness, cloud fraction, ozone concentration, and surface albedo. The second method, as implemented by NASA’s Ocean Biology Processing Group (OBPG) in the standard Ocean Color data processing chain, expresses the energy budget of the atmosphere-surface-ocean system via a simple radiative transfer model. The performance of these methods is evaluated using an extensive in situ PAR dataset collected in the Arctic Ocean between 1998 and 2014, with daily values ranging from 0.08 to 61.07 Em⁻² d⁻¹. A methodology is developed to compare in situ measurements and satellite products of different spatial and temporal resolution. Agreement is generally good between satellite-derived estimates and ship-based data and between methods. Specifically, both methods yield a small positive bias of 6% and 2% and a relative uncertainty larger than that observed at low latitude, with a root mean squared error (RMSE) of 33% and 20% for the LUT and OPBG methods, respectively. This is attributed to the peculiar environmental conditions encountered in the Arctic, namely low solar elevation, changing surface albedo due to sea ice, and persistent cloudiness. The RMSE difference among methods is due to the high temporal resolution (3 h) of the International Satellite Cloud Climatology Project (ISCCP) LUT input not fully compensating for its low spatial resolution (280 km grid cells). The LUT method has the major advantage of providing PAR estimates in all conditions, including ice-covered regions, while the OPBG method is currently limited to open waters and a solar zenith angle lower than 83°. Consequently, the OPBG method may not account for as much as 38% of PAR reaching the Arctic ocean surface annually. Both methods have the potential to provide useful PAR estimates just below the ice, by including information about ice transmittance.

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1. Introduction

Incident Shortwave Radiation (SW) at the Earth surface influences the atmospheric and oceanic circulation as well as the climate. At high northern latitudes, the most important parameters impacting SW are solar elevation, fog, cloud cover, and sea ice cover (Gorodetskaya & Tremblay, 2008; Zhao & Garrett, 2015; Zygmuntowska, Mauritsen, Quaas, & Kaleschke, 2012). With global warming, there is clear evidence that Arctic cloud cover is increasing during spring and summer months (Schweiger, 2004; Vavrus, Holland, & Bailey, 2010), while sea ice extent and thickness are decreasing (Stroeve et al., 2012). On the one hand, increasing clouds have resulted in dimming the SW flux reaching the sea surface (Wang & Key, 2005; Dutton et al., 2006). On the other hand, less sea ice allows more SW to penetrate the water column, creating a positive feedback that further accelerates sea ice melting (Perovich, Nghiem, Markus, & Schweiger, 2007).

Changes in SW also have implications on various key photobiological and photochemical processes that drive biogeochemical cycles. Through photosynthesis, phytoplankton harvest light to fix carbon dioxide (CO₂), synthesizing organic matter (OM) that fuels the marine food web (Platt & Jassby, 1976). Various photochemical reactions driven by energetic ultraviolet radiation (UVR) also have profound impact on OM cycling, as well as cell damage-repair processes in marine systems (Gao & Zepp, 1998; Mopper & Keiber, 2002; Morrow & Booth, 1997; Smith & Cullen, 1995; Zepp, Erickson, Paul, & Sulzberger, 2011). Based on satellite observations, several recent studies of the Arctic Ocean and its surrounding seas have attempted to quantify the impacts of...
environmental changes on phytoplankton photosynthesis (Arrigo, van Dijken, & Pabi, 2008; Bélanger, Babin, & Tremblay, 2013; Pabi, Van Dijken, & Bélanger, 2008) and photochemical processes (Bélanger et al., 2006; Tank, Manizza, Holmes, McClelland, & Peterson, 2012; Xie, Bélange, Song, Benner, Taalba, Blais & Lefouest, 2012).

To quantify photochemical and photobiological processes, accurate estimations of UVR and visible solar radiation are imperative. Current approaches to estimate solar radiation reaching the sea surface are based on satellite-derived observations and numerical modeling. However, the uncertainties in these satellite-based assessments remain to be quantified. The work presented here is motivated primarily by the need for an adequate Arctic representation of the day-to-day variations of UVR and photosynthetically active radiation (PAR), herein defined as the photosynthetic photon flux density in Einstein (E) (mole of photons) per unit area and unit time integrated over the 400 to 700 nm spectral range (Em⁻² s⁻¹ or Em⁻² d⁻¹). A remote access to synoptic and reliable PAR information is necessary, among other things, for most marine primary production (PP) assessment (Campbell et al., 2002; Lee et al., 2015; Morel, 1991; Platt & Sathyendranath, 1993), and therefore crucial towards precise and unbiased satellite-based PP estimation methods. A method that provides information on the spectral distribution of incident light is needed for applying spectrally-resolved PP models (Bélanger et al., 2013; Smyth, Tlstone, & Groom, 2005) and describing photochemical processes involving chromophoric dissolved OM (Bélanger et al., 2006; Xie, Bélanger, Demers, Vincent, & Papakryiakou, 2009; Xie et al., 2012; Song, Xie, Bélanger, Leymarie, & Babin, 2013).

Satellite-based surface irradiance estimations are available from various Earth observing programs, but are often unreliable at high latitudes. For example, Zhang et al. (2013) pointed out that the shortwave flux of the Global Energy and Water Cycle Experiment Surface Radiation Budget (GEWEX-SRB) dataset has large uncertainties in polar areas. Due to confusion between sea ice and clouds, the Ozone Monitoring Instrument (OMI) Surface Solar Irradiance (SSI) product excludes data at high latitudes (Wang, Liu, Chance, González, & Chan, 2014). The Earth System Science Workbench (ESSW) only estimated PAR below 60° N. The Total Ozone Mapping Spectrometer (TOMS) PAR product is limited to latitudes lower than 66° N (Eck & Dye, 1991). Many of those products are no longer operational and not suitable for Arctic applications primarily because of limited spatial coverage. Alternatives such as using routinely derived global total SW irradiance to estimate visible flux exist, but the conversion from SW to PAR is contingent on uncertainties due to atmospheric composition (e.g., water vapor, clouds, aerosols, etc.) (Baker & Frouin, 1987; Frouin & Murakami, 2007; Pinker & Laszlo, 1992). The Surface and Atmospheric Radiation Budget (SARB) product from the Clouds and the Earth’s Radiant Energy System (CERES) (Wielicki et al., 1996) can be converted to PAR (Su, Charlock, Rose, & Rutan, 2007) and performs relatively well over land-based mid-latitude stations with relative bias from in situ measurements ranging from 1.4% to 9.3%, but to our knowledge no one has evaluated it over the Arctic.

NASA’s Ocean Biology Processing Group (OBPG) produces instantaneous and daily averaged PAR quantities on an operational basis using low Earth orbit (LEO) satellites designed to quantify ocean color (e.g., Sea-Wide-Field-of-View Sensor (SeaWIFS) and the Moderate Resolution Imaging Spectroradiometers MODIS-AQUA and MODIS-TERRA) (Frouin, Franz, & Werdell, 2003). Processing such multispectral radiometric measurements at high latitudes implies strict conditions. First, the availability of the data is restricted by solar elevation. In fact, NASA OBPG PAR product is limited to solar zenith angles < 83° (has of Oct. 2015). This limitation means NASA OBPG PAR quantities are not available for >61% of the annual time at latitudes above the circumpolar Arctic Circle. Second, no PAR estimate is available when > 10% of a pixel is occupied by sea ice (as derived from passive microwave data). Third, the temporal binning used to produce Level 3 (L3) time-composite PAR products compromises accuracy yet does not systematically solve the gaps in the Arctic region, resulting in many binned pixels with no information or severe bias. As a result, PAR estimates at high latitudes can be unrepresentative of the true central tendency.

Due to limitations outlined above, Bélanger and co-workers proposed an alternative method to estimate spectrally-resolved downwelling solar irradiance at the ocean surface (hereafter denoted as Ed(λ) where λ stands for wavelength) for all atmosphere and sea ice conditions. The methods was developed to feed spectrally-resolved photochemical models going down to 290 nm in the UV-B domain (Song et al., 2013; Xie et al., 2009, 2012), as well as spectrally-resolved phytoplankton photosynthesis models (Bélanger et al., 2013; Le Fouest et al., 2011; Tremblay et al., 2011).

The main objective of the present study is to quantify the uncertainty and potential biases of Bélanger’s method, as well as the OBPG method, using an extensive in situ data set of surface irradiance gathered from various research cruises conducted in Arctic waters (Fig. 1-1,2). Because most in situ measurements were made with quantum PAR sensors, we limit our evaluation to this spectrally-integrated quantity. In addition, the evaluation is particularly challenging since in situ measurements are instantaneous and punctual in space, while satellite-based estimation is spatially-integrated and sometime time-integrated. Consequently, we further examine the temporal and spatial variability of incident radiation. To complete the evaluation, satellite products generated using the two methods are compared (Fig. 1-3).

2. Satellite-based methods to estimate surface solar irradiance

2.1. Look-up-table (LUT) approach

Bélanger and co-workers developed a method for estimating incident spectral irradiance in all atmosphere and sea surface conditions using a look-up-table (LUT) approach. The method yields a downwelling irradiance spectrum, Ed(λ), at the sea surface for a given set of input parameters, namely the solar zenith angle (SZA), cloud optical thickness (τcl), cloud fraction (CF), ozone concentration (O3) and sea ice concentration (SIC). The method employs precomputed LUT of Ed(λ) that is interpolated for the current set of input parameters (hereinafter referred as the LUT method). This section describes the LUT generation and its interpolation to obtain the final Ed(λ, SZA, τcl, CF, O3, SIC), just above (0°) or below (0°) the air-sea interface.

2.1.1. LUT generation

Ed(λ) LUT was generated using the radiative transfer model SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer; Ricchiazzi, Yang, Gautier, & Sowle, 1998). SBDART model was used since it has been tested extensively over the years (Su, Charlock, & Rose, 2005; Su et al., 2007). Simulations were made for 19 values of SZA (0 to 90°), 8 τcl (0 to 64), 10 O3 (100 to 50) Dobson Units (DU)) and 7 surface albedo (A0) (0.05 to 0.85), yielding a total number of 10,640 downwelling irradiance spectra covering the spectral range from 290 nm to 700 nm at 1 or 5 nm resolutions (N λ = 83 or 401). Note that the previous version of the LUT (Bélanger et al., 2013) did not account for the variability...
in $A_\text{ba}$, which was kept constant at 8% (see discussion below). Total solar irradiance at the top of the atmosphere was taken to be 1366.7 W m$^{-2}$ (Thullier et al., 2003). Marine aerosols (Shettle & Fenn, 1979) with an optical thickness of 0.05 at 550 was kept constant. This value of aerosol optical thickness represents a climatology established from sun photometer measurements made at Barrow (71.3° N; 156.8° W) (Tomasi et al., 2012). A subarctic summer standard atmosphere was selected to depict typical maritime pressure, temperature and water vapor profiles (McClatchey, Fenn, Selby, Volz, & Garing, 1971).

SBDART computes both direct and diffuse components of the downwelling irradiance above the sea surface $Ed(0^+;\lambda)$, which are used to compute the downwelling irradiance just below the sea surface $Ed(0^-;\lambda)$. The diffuse component of $Ed(0^-;\lambda)$ was multiplied by 0.934 to account for the specular reflection at the sea surface (6.6%, (Morel, 1991)). The direct component of $Ed(0^-;\lambda)$ was multiplied by 1 minus the Fresnel reflection coefficient calculated using Gregg and Carder (1990)'s formulation for a wind speed of 4 m s$^{-1}$. For evaluation purposes, a second LUT was generated for the downwelling irradiance just above the sea surface $Ed(0^-;\lambda)$ by summing the direct and diffuse components of $Ed$. The downwelling irradiance (Wm$^{-2}$ nm$^{-1}$) was converted into photon flux (E m$^{-2}$ nm$^{-1}$) before it was stored in the LUTs. The 5-dimensional $Ed$ LUTs ($\lambda$, SZA, $\tau_\text{cl}$, $\tau_\text{d}$, $\tau_\text{a}$) at 5 nm and 1 nm spectral resolutions comprise 883,120 and 4,266,640 elements, respectively. The next section explains how the LUT is used to obtain $Ed$ for a given time and pixel location.

### 2.1.2. LUT interpolation

The LUT can be interpolated to get $Ed(\lambda)$ for any combination of inputs, i.e. SZA, $\tau_\text{d}$, $\tau_\text{cl}$, and $A_\text{s}$, as long as their values fall within the range of input parameters defined above. In general, large ocean pixels are partly cloudy, therefore the cloud fraction (CF) over the surface must be accounted for. To calculate the downwelling irradiance for a given ocean pixel, the $Ed(\lambda)$ is calculated by summing with respect to CF. $Ed(\lambda)$ is obtained from the LUT by assuming $\tau_\text{d}$ equal to 0. $Ed(\lambda)$ and $Ed(\lambda)$ are then added together to form the downwelling irradiance above (or below) the sea surface.

$$Ed(\lambda) = Ed(\lambda) \times CF + Ed(\lambda) \times (1-CF) \tag{1}$$

Both $Ed(\lambda)$ and $Ed(\lambda)$ are obtained from the LUT for the given set of SZA, $\tau_\text{d}$, $\tau_\text{cl}$, and $A_\text{s}$ using a full quadratic-linear interpolation scheme. SZA is simply calculated for a given time and position on Earth, while other inputs are obtained from satellite observations. For the surface albedo assumptions need to be made. In high northern latitudes, presence of sea ice and low sun elevation significantly increase $A_\text{c}$. Here we estimate $A_\text{c}$ by accounting for SIC. Assuming an ocean albedo of 0.06 (Frouin & Chertock, 1992), the surface albedo was calculated as follow:

$$A_\text{c} = 0.06 \times (1-SIC) + A_\text{ice}(DOY) \times SIC \tag{2}$$

where $A_\text{ice}(DOY)$ is the sea ice albedo that varies as a function of the day of year following the data reported by Perovich et al., 2007; their (Fig. 3), and SIC is the fractional sea ice concentration within a pixel provided by satellite passive microwave observations.

### 2.2. OBPG approach

OBPG estimates daily PAR from ocean color satellites following Frouin et al., 2003. The method employs an energy budget approach. Briefly, the energy reaching the surface is the initial flux that was not reflected nor absorbed by the atmosphere-surface system. The PAR model, based on Frouin and Chertock (1992), uses plane-parallel theory and assumes that cloud and atmospheric component can be decoupled with no absorption by clouds in the visible portion of the solar spectrum. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer and the solar flux reaching the surface is

$$Ed = \frac{E_{\text{clear}}(1 - A)}{1 - A_\text{s}} \tag{3}$$

where $A$ is the albedo of the cloud-surface system and $A_\text{s}$ is the albedo of the ocean surface, $E_{\text{clear}}$ being the energy that would reach the surface in the absence of clouds if the surface were not reflecting. In order to express $A$ as a function of the radiance measured in the PAR spectral range by the satellite sensor, radiometric measurements are converted into reflectance using the incoming solar irradiance. This reflectance is corrected for the effect of atmospheric transmission through absorption (ozone and water gases) and scattering (molecules and aerosols) in the atmosphere. Albedo of the cloud-surface system is then obtained by transforming the resulting spectral reflectance into albedo. This is accomplished using a typical cloud bidirectional function for the cloudy fraction of the reflectance, noting that $A \approx CF \times A_\text{c} + A_\text{s}$, where $A_\text{c}$ is cloud albedo. All values are weighted and normalized by the extraterrestrial solar irradiance and averaged over the PAR spectral range. They are then integrated over day length according to SZA to yield a daily averaged PAR value. The observed measurement at the moment of the satellite overpass is assumed to be representative of cloud conditions during the day. When several observations are acquired over a given target (or pixel), the individual daily estimates from 0:00 to 24:00 UTC are weight-averaged using the cosine of SZA. This algorithm was originally conceived for SeaWiFS but has been generalized to operate on any ocean color sensor with enough visible bands that do not saturate over clouds (e.g., MODIS).

### 3. Data and methods

#### 3.1. In situ measurements

#### 3.1.1. Field campaigns

Several field programs collected continuous PAR measurements ranging from 50°N to 80°N in the Arctic from 1998 to 2014 (Table 1). The oceanographic programs include the North Water polynya (NOW), Canadian Arctic Shelf Exchange Study (CASES), MALINA, and VITALS.

<table>
<thead>
<tr>
<th>Cruise or program</th>
<th>Year</th>
<th>Instrument</th>
<th>Measurements</th>
<th>Months</th>
<th>Number of days</th>
</tr>
</thead>
<tbody>
<tr>
<td>The NOrth Water (NOW)</td>
<td>1998</td>
<td>LI-COR 192SA$^a$</td>
<td>PAR</td>
<td>4.6</td>
<td>32</td>
</tr>
<tr>
<td>1999</td>
<td>LI-COR 192SA$^a$</td>
<td>PAR</td>
<td>8–10</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Canadian Arctic</td>
<td>2003</td>
<td>GUV-510$^b$</td>
<td>PAR</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Shelf Exchange Study (CASES)</td>
<td>2004</td>
<td>GUV-510$^b$</td>
<td>PAR</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>MALINA</td>
<td>2009</td>
<td>PARLite$^e$</td>
<td>PAR</td>
<td>8</td>
<td>23</td>
</tr>
<tr>
<td>TARA OCEAN</td>
<td>2013</td>
<td>C-OPS$^d$</td>
<td>Spectral</td>
<td>5–12</td>
<td>105</td>
</tr>
<tr>
<td>VITALS</td>
<td>2014</td>
<td>C-OPS$^d$</td>
<td>Spectral</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>ArcticNet (AN)</td>
<td>2013</td>
<td>LI-190SA$^a$</td>
<td>PAR</td>
<td>8–10</td>
<td>56</td>
</tr>
<tr>
<td>2006</td>
<td>LI-190SA$^a$</td>
<td>PAR</td>
<td>9</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>LI-190SA$^a$/PARLite$^e$</td>
<td>PAR</td>
<td>8,10–11</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>LI-190SA$^a$/PARLite$^e$</td>
<td>PAR</td>
<td>8–9</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>LI-190SA$^a$/PARLite$^e$</td>
<td>PAR</td>
<td>7–11</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>LI-190SA$^a$/PARLite$^e$</td>
<td>PAR</td>
<td>7–10</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>LI-190SA$^a$/PARLite$^e$</td>
<td>PAR</td>
<td>7–10</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>C-OPS$^d$/PARLite$^e$</td>
<td>Spectral/PAR</td>
<td>8–10</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>C-OPS$^d$</td>
<td>Spectral/PAR</td>
<td>8–9</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Data provided by Dr. Michel Gosselin (UQAR).
$^b$ Data provided by Dr. Serge Demers (UQAR).
$^c$ Data provided by Dr. Tim Papakiriakou (U. of Manitoba).
$^d$ Data provided by Dr. Stan Hooker (NASA).
$^e$ Data provided by Dr. Marcel Babin (Laval University).
$^f$ Data provided by Dr. Simon Bélanger (UQAR).
ArcticNET, TARA Oceans Polar Circle and Ventilation, Interactions and Transports Across the Labrador Sea (VITALS). The field data were collected while the schooner (TARA Oceans Polar Circle) or the icebreakers were sailing in both open waters and variable sea-ice cover conditions. Most observations were from late summer to autumn (Fig. 2), which is a period of the year where persistent cloud cover is usually encountered in the Arctic (Chernokulsky & Mokhov, 2012).

3.1.2. Data processing

Instruments were calibrated by the manufacturer before each cruise. All instruments were cleaned on a regular basis and were recording PAR continuously (at 1 to 15 min intervals) throughout the field campaigns, providing detailed diurnal and seasonal variability of incoming light in Arctic. This extensive dataset (837 days of observation) is used as a reference to evaluate the satellite-based irradiance estimation methods and to study its natural variability in the Arctic. To control the quality of the data, the daytime solar zenith angle (SZA) was plotted together with PAR measurements (Fig. 3A) and a scatter plot of PAR vs SZA was examined (Fig. 3B) to detect possible errors. For any given day, if two distinct curve shapes in SZA vs PAR were observed between sunrise and sunset, the daily PAR was flagged and further examined. Days containing gaps or obvious outliers were screened out.

Moreover, data collected at sea sometimes suffered from shadows or reflection resulting from ship structure (e.g., communication towers). On-board precautions were taken to avoid contamination from external influences on natural light. In order to assess such uncertainties sources, during 7 cruises out of 16 (ArcticNET 2007–2011, 2013 and MALINA), 2 sensors were positioned at distant locations on the ship. The examination of the difference in PAR recorded under different conditions allowed rigorous quality control and efficient elimination of outliers. A total of 704 days of observations out of 837 (84%) passed the quality control tests.

3.2. Satellite data

3.2.1. Atmosphere and sea ice

In this study, as well as in our previous studies (Bürlanger et al., 2013; Tremblay et al., 2011; Song et al., 2013; Xie et al., 2009, 2012), atmospheric parameters (i.e., $\tau_a$, $O_3$, and CF) needed to interpolate the $E_d$ LUT were obtained from the International Satellite Cloud Climatology Project (ISCCP; Rossow & Schiffer, 1991). ISCCP produced a 26 year long (1983 to 2009) time series at 3 h time steps, on a global equidistant grid of 280 km resolution, distributed as a radiative flux profile data set (ISCCP-FD-SFR) that includes the atmospheric inputs of interest used to interpolate the LUT (Zhang, Rossow, Lacis, Oinas, & Mishchenko, 2004). The total column ozone amounts are from the Total Ozone Mapping Spectrometer (TOMS, Version 7), while clouds properties (c.f., $\tau_c$ and CF) were calculated using infrared observations provided by geostationary meteorological satellites for latitudes $>60^\circ$ (Meteosat, GOES, GMS and Insat, (Desormeaux, Rossow, Brest, & Campbell, 1993) and Advanced Very High Resolution Radiometer poleward (AVHRR) (Schweiger, Lindsay, Key, & Francis, 1999) on board of polar-orbiting meteorological NOAA satellites for latitudes $>60^\circ$. Sea ice concentration, which is used to estimate $A_s$, was obtained from the National Snow and Ice Data Center (NSIDC). SIC were derived from the SMMR and DMSP SSM/I-SSMIS passive microwave observations (1984 to 2007) (Cavalieri, Parkinson, Gloersen, & Zwally, 1996), and near-real-time DMSP SSMIS observations (Maslanik & Stroeve, 1999).

3.2.2. Ocean color

Daily PAR data derived using the method described in Section 2.2 from ocean color sensors SeaWiFS, MODIS-Aqua, and MODIS-Terra were obtained from the OPBG web browser at the level 3 (http://oceancolor.gsfc.nasa.gov/cgi/l3). The OBPG product used here represents the average value of the PAR geophysical variable over the length of 24 h. The algorithm in use generates daily PAR values from all available satellite passes directly converted to daily PAR. As indicated above, L2 daily PAR for each satellite overpass are binned with a weighted mean based on the cosine of the solar zenithal angle to produce L3 daily PAR product (Patt et al., 2003). In the present OBPG PAR processing scheme, three criteria may prevent PAR from being produced over the ocean: 1) the presence of high sun glint at the air-sea interface, 2) a SZA larger than 83°, and 3) SIC larger than 10% at the pixel. A combination of SeaWiFS, MODIS-Aqua and MODIS-Terra should account for the diurnal variability of the clouds and considerably reduce the satellite biases. MODIS-Aqua has an ascending equatorial crossing time of 13:30 (local solar time), while MODIS-Terra and SeaWiFS have descending equatorial crossing time of 10:30 and noon, respectively. Therefore, MODIS-Aqua, MODIS-Terra and SeaWiFS L3 daily products (9.28 km) were merged with a simple median function.

3.3. Comparison of satellite products and in situ data

Satellite-based estimates of PAR are matched in the temporal and spatial frame shared with the available in situ data. The evaluation of the LUT and OBPG methods through separate matchup exercises is conducted to account for the environmental variability. Since the in situ data were acquired on moving ships, hourly estimates of $E_d(\lambda)$ from the LUT are computed with respect to the ship position and time. Because the ISCCP data are distributed on a 280 km resolution grid at a 3 h time interval, the atmospheric inputs are interpolated both in space (bi-linear) and time for any given ship position and time. For that given position and time, $A_s$ is calculated using Eq. (2) with SIC of the nearest neighbor 25 km resolution pixel and assumed constant during the day (daily SIC are used). The instantaneous output $E_d(\lambda)$ from the interpolated LUT was numerically integrated from 400 to 700 nm to obtain PAR. Finally, the daily PAR was generated with a trapezoid integration of the 24 instant hourly estimates (UTC).

Since the OBPG method was designed to produce PAR on a daily scale, and that we cannot distinguish the spatial from the temporal variability with the in situ dataset, the matchup exercise was only relevant if the environmental variability within a given day of sampling was weak (hereafter referred to as intraday variability). To evaluate the intraday variability during a day of in situ measurements, we extracted daily PAR from OBPG for each hourly position visited by the ship during day time (i.e. SZA < 90°). In other words, for a given day of in situ PAR measurements on a moving ship, up to 24 daily PAR estimates were obtained from OBPG for that day. Then the intraday variability was assessed using the coefficient of variation ($C_{\text{intraday}}$), calculated as

$$C_{\text{intraday}}(\%) = 100 \times \frac{\sigma_{\text{PAR}}}{\overline{\text{PAR}}} \times \overline{\text{PAR}}^{-1}$$

where $\sigma_{\text{PAR}}$ is the standard deviation of the N ≤ 24 daily PAR estimates and $\overline{\text{PAR}}$ is the mean daily PAR for that day. If the ship remained at the same position during the whole day (or within a given 4.64 or 9.28 km pixel), for example, $C_{\text{intraday}}$ would be equal to 0% ($N = 1$, $\sigma_{\text{PAR}} = 0$), because only one pixel would be concomitant in space with all the ship's positions. In contrast, if the ship was transiting in open waters over several km during summer time, up to 24 OBPG pixels were used to compute $C_{\text{intraday}}$. Therefore, $C_{\text{intraday}}$ is essentially a measure of the spatial variability of PAR during a given day of data acquisition. For example, under discontinuous cloud cover, $C_{\text{intraday}}$ could reach values as high as 50%. In such cases, the PAR evaluation may be irrelevant (see Section 4.2 for more details). We considered this variability when daily in situ PAR was compared to the mean OBPG PAR values obtained from the pixels encountered during day time.
3.4. Evaluation metrics

To evaluate the performance of the algorithms, the mean bias (systematic error) and the root mean squared error (RMSE) were calculated. These metrics are considered sufficient for comparison with other studies. Mean absolute difference is similar to RMSE and in our case do not provide supplementary information for our analysis. These errors are defined as follows:

\[
\text{BIAS} = \frac{1}{N} \sum (\text{PAR}_{\text{estimated}} - \text{PAR}_{\text{in situ}})
\]

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum (\text{PAR}_{\text{estimated}} - \text{PAR}_{\text{in situ}})^2}
\]

The bias and RMSE were also normalized by the average PAR\text{in situ} and express in relative unit (%) to facilitate comparison. Finally, we applied a major axis (MA) regression model of type II (R package lmder2 (Legendre, 2014)) to estimate the slope (S) and the intercept (I) of the linear regression. We examined whether we can reject the null hypothesis that S and I are unity and zero, respectively, at a significance level of 0.05.

4. Results

4.1. Evaluation of LUT method

Arctic in situ daily PAR observations exhibited a wide range of natural variability (> three orders of magnitude). The maximum in situ PAR value (61.07 Em\textsuperscript{-2} d\textsuperscript{-1}) was observed around the summer solstice and the minimum value (0.08 Em\textsuperscript{-2} d\textsuperscript{-1}) was in mid-autumn. A relatively good agreement was seen between in situ daily PAR and LUT estimates with a high coefficient of determination \((R^2 = 0.881)\) for all matchups (Table 2). In fact, 318 days of observations out of 490 passed the quality control test for the period, which was restricted to 1998–2009 corresponding to ISCCP data availability. Due to the temporal bias in our in situ data set towards late summer and autumn (Fig. 2), more matchup days are available for relatively low in situ PAR values (median = 10.99 E m\textsuperscript{-2} d\textsuperscript{-1}). The slope (1.033) and the intercept (0.350) of the linear regression (Type II, major axis) were not significantly different from 1 and 0, respectively, \((p > 0.05)\). The model was, however, positively biased (6%), suggesting an overall overestimation of the predicted values (Fig. 4). The RMSE reached 4.952 E m\textsuperscript{-2} d\textsuperscript{-1}, which gave a relative uncertainty of 33%. Finally, 63% of the matchups are within 30% of error and 81% are within 50% of error. When restricting the evaluation period from 1998 to 2014, as mentioned above, this is because OBPG does not calculate PAR in presence of sea ice or when the sun is low on the horizon. In addition, only 110 days out of 208 were characterized by a negligible intraday variability, i.e., when the coefficient of variation \((\text{CV}_{\text{intraday}} = 2\%\)) for daily PAR extracted from the ship location during a given day was below 10%. To illustrate the intraday variability concept, Fig. 5 presents two matchup days showing low and high \text{CV}_{\text{intraday}} respectively. The top panels show the hourly positions of the ship during the two selected days in northern Baffin Bay (left; August 21, 2005) and Hudson Bay (right; August 9, 2007). The total distances travelled during these days were 301 and 402 km, respectively. The day in Baffin Bay clearly exhibited a small intraday variability for the three ocean colors satellites \((\text{CV}_{\text{intraday}} = 2\%)\) (Fig. 5b; left). In contrast, inhomogeneous cloud cover along the 400 km transect in Hudson Bay created large differences in daily PAR (up to a factor of three) derived from each sensor (Fig. 5b; right). Part of the difference is probably due to the different orbit characteristics, which results in the observation of the same location at different times of the day. In addition, large differences in the mean daily PAR \((\text{CV}_{\text{intraday}} = 27\%\)) appear along the transect due to combined spatial and temporal variability in cloud cover. This variability is partly captured by the 3 h resolution of the ISCCP inputs (Fig. 5c). Both days showed variable cloud fraction ranging from 0.20 to 0.75, but the variability was clearly smaller in Baffin Bay. The cloud optical thickness was smaller in Baffin Bay (\(<20\)) compared to that observed in Hudson Bay (\(>20\)). As expected the observed short-term variability in instant PAR was generally higher than that captured by the satellite-based estimates from the LUT (Fig. 5d). In Hudson Bay, the presence of thick clouds between 12:00 and 15:00 UTC dimmed PAR, followed by an abrupt increase in PAR around 15:00 UTC. This diurnal pattern was partly captured by the LUT method using ISCCP inputs.

Table 2 Performance of the satellite-derived daily PAR estimates. Statistics are provided for the whole matchups and various subsets (see text).

<table>
<thead>
<tr>
<th>Method</th>
<th>N</th>
<th>Bias</th>
<th>RMSE</th>
<th>Slope*</th>
<th>Intercept*</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUT</td>
<td>318</td>
<td>0.853 (6%)</td>
<td>4.952 (33%)</td>
<td>1.033</td>
<td>0.350</td>
<td>0.881</td>
</tr>
<tr>
<td>LUT (SIC &gt; 10%)</td>
<td>136</td>
<td>0.793 (7%)</td>
<td>4.454 (38%)</td>
<td>1.012</td>
<td>0.645</td>
<td>0.813</td>
</tr>
<tr>
<td>LUT (Dist. &lt; 30 km)</td>
<td>116</td>
<td>0.256 (2%)</td>
<td>4.464 (30%)</td>
<td>1.001</td>
<td>0.244</td>
<td>0.913</td>
</tr>
<tr>
<td>OBPG</td>
<td>208</td>
<td>0.456 (2%)</td>
<td>5.227 (20%)</td>
<td>0.927</td>
<td>2.360</td>
<td>0.886</td>
</tr>
<tr>
<td>OBPG (C.V. &lt; 20%)</td>
<td>168</td>
<td>0.669 (2%)</td>
<td>5.155 (19%)</td>
<td>0.932</td>
<td>2.522</td>
<td>0.900</td>
</tr>
<tr>
<td>OBPG (C.V. &gt; 10%)</td>
<td>110</td>
<td>0.799 (3%)</td>
<td>5.319 (18%)</td>
<td>0.916</td>
<td>3.355</td>
<td>0.906</td>
</tr>
<tr>
<td>OBPG (Dist. &lt; 30 km)</td>
<td>53</td>
<td>-0.093 (0%)</td>
<td>4.466 (17%)</td>
<td>0.892</td>
<td>2.675</td>
<td>0.931</td>
</tr>
</tbody>
</table>

* The slope and intercept were calculated using a type 2 regression and numbers in bold are significantly different from 1 and 0, respectively, at \(p < 0.05\).

4.2. Evaluation of OBPG method

Out of the 704 daily in situ PAR, 208 matchups were found for the period from 1998 to 2014. As mentioned above, this is because OBPG does not calculate PAR in presence of sea ice or when the sun is low on the horizon. In addition, only 110 days out of 208 were characterized by a negligible intraday variability, i.e., when the coefficient of variation \((\text{CV}_{\text{intraday}} = 2\%\)) for daily PAR extracted from the ship location during a given day was below 10%. To illustrate the intraday variability concept, Fig. 5 presents two matchup days showing low and high \text{CV}_{\text{intraday}} respectively. The top panels show the hourly positions of the ship during the two selected days in northern Baffin Bay (left; August 21, 2005) and Hudson Bay (right; August 9, 2007). The total distances travelled during these days were 301 and 402 km, respectively. The day in Baffin Bay clearly exhibited a small intraday variability for the three ocean colors satellites \((\text{CV}_{\text{intraday}} = 2\%)\) (Fig. 5b; left). In contrast, inhomogeneous cloud cover along the 400 km transect in Hudson Bay created large differences in daily PAR (up to a factor of three) derived from each sensor (Fig. 5b; right). Part of the difference is probably due to the different orbit characteristics, which results in the observation of the same location at different times of the day. In addition, large differences in the mean daily PAR \((\text{CV}_{\text{intraday}} = 27\%\)) appear along the transect due to combined spatial and temporal variability in cloud cover. This variability is partly captured by the 3 h resolution of the ISCCP inputs (Fig. 5c). Both days showed variable cloud fraction ranging from 0.20 to 0.75, but the variability was clearly smaller in Baffin Bay. The cloud optical thickness was smaller in Baffin Bay (\(<20\)) compared to that observed in Hudson Bay (\(>20\)). As expected the observed short-term variability in instant PAR was generally higher than that captured by the satellite-based estimates from the LUT (Fig. 5d). In Hudson Bay, the presence of thick clouds between 12:00 and 15:00 UTC dimmed PAR, followed by an abrupt increase in PAR around 15:00 UTC. This diurnal pattern was partly captured by the LUT method using ISCCP inputs.

Measured daily PAR in the Baffin Bay reached 30.2 compared to 26.0 Em\textsuperscript{-2} d\textsuperscript{-1} for the LUT method. For comparison, the OBPG PAR along the 301 km transect varies within a relatively narrow range of 29.9 to 32.2 Em\textsuperscript{-2} d\textsuperscript{-1}, with a mean of 31.1 Em\textsuperscript{-2} d\textsuperscript{-1}. If the mean is restricted to daytime (Fig. 5b, black curves), the PAR remained the same. In Hudson Bay, the in situ PAR was 35.1 compared to 32.4 and 55.1 Em\textsuperscript{-2} d\textsuperscript{-1} for the LUT method and the clear sky simulation, respectively. For this particular day, the PAR along the ship transect derived from OBPG varies by nearly a factor of 2 (28.3 to 47.5 with a mean of 39.7 Em\textsuperscript{-2} d\textsuperscript{-1}; Fig. 5b right). However, if we averaged the PAR for daytime only (Fig. 5b, black curves), the OBPG estimate (37.4 Em\textsuperscript{-2} d\textsuperscript{-1})
falls closer to the in situ observation. These results suggest the evaluation of the performance of the OBPG using a moving ship will depend upon the spatial variability of the cloud cover encountered along its course during a given day.

Fig. 6 displays the scatter plot of in situ versus OBPG PAR estimates for the matchups available for the 1998–2014 period. When considering all available matchups (N = 208), we obtained a weak positive bias of 2% and a RMSE of 20%. The relative RMSE slightly improved when matchups showing high intraday variability are excluded from the analysis (Table 2). On average the intraday variability (CV\textsuperscript{intraday}) computed using OBPG daily PAR estimate between sunrise and sunset was 12%, and 91% of the matchups (N = 190) showed a CV\textsuperscript{intraday} lower than 30%. When only matchups with negligible intraday variability are considered (CV\textsuperscript{intraday} < 10%; N = 110), the bias increases to 3% and RMSE was lowered to 18%, while the R\textsuperscript{2} increase to 0.906. Finally, we also computed the statistics for days when ship displacement was minimal (i.e., <20 km; N = 41), and found even better performance of the OBPG method in terms of bias (0%) and RMSE (17%) with high coefficient of determination (R\textsuperscript{2} = 0.931), but with a slope significantly lower than 1 (S = 0.892) and an intercept significantly higher than 0 (I = 2.675).

4.3. LUT versus OBPG methods

In this section, we compare the two satellite-based methods to estimate daily PAR. First we examine the typical spatial variability given by each method. On one hand, the LUT method uses as input ISCCP cloud products at 280 km. OBPG uses averaged ocean-color satellite observations (L3) on a 4.6 km resolution grid. The PAR spatial variation within a 280 km pixel of the ISCCP grid is assessed using MODIS-A and MODIS-T merged products, which are considered to reflect the true spatial variability at this spatial scale. For this exercise, we selected an ISCCP pixel in the Norwegian sea located Northeast of Iceland (Fig. 7, inset). The 580 4.6 km MODIS pixels falling within an ISCCP pixel were extracted for each day of the month of July 2004. PAR from LUT method was calculated using the ISCCP data interpolated both in space and time for each MODIS pixel centroids (see Section 2.1).

Spatial PAR variability, as represented by the error bars in Fig. 7, is much greater for MODIS (CV = 26%) than the one obtained from the LUT method (CV = 7%). As expected, based on the ISCCP’s pixel resolution (280 km), the bilinear interpolation will always give a smooth distribution of pixel values. It is thus not precisely describing the locally varying conditions (e.g., situation of heterogeneous cloud cover) as the OBPG method or the in situ data do. On average, 19% of the CV is not accounted for with the LUT method interpolation and the differences can reach up to 35% in certain cases.
5. Discussion

5.1. Comparison of performance by various studies

Here we compare the performance of the two satellite-based methods evaluated in this study (Table 2) to the performance obtained by satellite products at lower latitudes. Several PAR models based on satellite observations have been published in the last decades (e.g., Bouvet, Hoepfner, & Dowell (2002); Carder, Chen, & Hawes (2003); Frouin & Chertock (1992); Frouin et al. (2003); Frouin & Murakami (2007); Frouin & McPherson, Ueyoshi, & Franz, 2013).

A preliminary assessment of the SeaWiFS PAR products was published in the NASA SeaWiFS Technical Report Series (Patt et al., 2003; Frouin et al., 2003). In situ data were obtained from two moored buoys sites: off the west coast of Canada (Halibut bank, 49.34°N); and the central Pacific (0° N). On average the bias was 2.2 Em^-2 d^-1 (5.3%) and the RMSE was 6.2 Em^-2 d^-1 (15%). When the data were integrated over time (8-days, monthly), the bias remained the same but the RMSE dropped to 8%. More recently, Frouin et al. (2013) evaluated OBPG PAR products using the in situ measurements collected during 2005–2010 at the CERES Ocean Validation Experiment (COVE) site located off Chesapeake Bay in the North Atlantic (36.9°N). They found RSME ranging from 6.3(20%) to 6.8 Em^-2 d^-1 (21%) with relatively high R^2 (0.855 to 0.883) for the sensor taken individually (i.e. SeaWiFS, MODIS-A and MODIS-T). Interestingly, the PAR estimates from all sensors exhibited a positive bias, ranging from 1.8(6%) (MODIS-A) to 2.8 Em^-2 d^-1 (%) (SeaWiFS). An improved performance was obtained when PAR from the three sensors were averaged, which augments the number of satellite overpasses during a given day (bias = 1.4 Em^-2 d^-1 (4%), RMSE = 4.6 Em^-2 d^-1 (14%); R^2 = 0.925). When PAR was integrated over time (week or month), the performance of the satellite-based improved in terms of RMSE (<3.3Em^-2 d^-1 (10%)) and R^2 (>0.968), but the positive bias remained unchanged (Frouin et al., 2013). In the OBPG method, the effects of the clear atmosphere and of the cloud-surface layer are decoupled, and the cloud-surface layer is assumed to be located below the clear atmosphere. Consequently, the correction of scattering by molecules and aerosols in the presence of clouds may be too large, yielding a lower cloud-surface albedo, therefore a higher PAR. In clear sky and open water situations, the SZA drives the PAR and the estimates error should be really small. Comparisons in these situations (not shown) suggests the possibility of calibration errors, which would contribute to the bias.

Conjointly, our evaluation of the OBPG method reveals a small positive bias of 0.5 Em^-2 d^-1 (2%). The LUT method also shows a positive bias 0.9 Em^-2 d^-1 (6%). However, most of the positive bias of both methods disappeared when the evaluation was performed using matchups for which the ship was more or less stationary (i.e., ship travel distance <30 km). It is therefore not clear whether the positive bias is due to the fact that we used a moving vessel rather than a fixed platform. While no definitive explanation is offered, it could be due to spatial and temporal variability of cloudiness and surface albedo, and/or to model uncertainties.

Bouvet et al. (2002) developed a method based on the Gregg and Carder (1990) model that uses as input several satellite-derived variables (TOA reflectivity, water vapor content, aerosol optical thickness and angstrom exponent, wind speed) and climate model parameters (pressure and relative humidity). Based on in situ measurements from two array systems of moored buoys in the equatorial and tropical regions, a RMSE of 5.2% were obtained for their monthly PAR estimates. Our results cannot be directly compared to these results as the time-integration over a month necessarily improved the model performance, as shown by Frouin et al. (2013). However, it is unlikely that the RMSE obtained for both OBPG and LUT methods would drop to value as low as 5% with a monthly integration.

Higher uncertainty obtained in our study (i.e., 17–20% for the OBPG method and 30–38% for the LUT method) may be due to a number of factors. As a first consideration, we would expect that the evaluation method itself, based on ship-borne measurements, increases the uncertainty associated with the methods. A second consideration would be that part of the higher uncertainty may result from the specific environmental conditions encountered in the Arctic.
Fig. 5. Examples of diurnal variability of modeled and measured irradiance, and environmental conditions along the ship track for two contrasting situations. On the left hand side, observations were made on August 21st (day 233) 2005 in northern Baffin Bay. On the right hand side, observations were made on August 9th (day 221) 2007 in Hudson Bay. Panels depict: a) 24 hourly ship position along the transects; b) the retrieved daily PAR values from MODIS-Aqua (squares), MODIS-Terra (circles), SeaWiFS (triangles) and the mean of the three (thick black line); c) interpolated ISCCP parameters (yellow: O$_3$/1000, black: CF and thickness the $\tau_{cl}$) for each time and position and surface albedo (blue) calculated using nearest neighbor SIC; d) measured instant PAR (solid line) and its corresponding estimate using the LUT method (dashed line) with inputs presented in c), and the clear sky radiative transfer simulation computed with local conditions (dotted line).
5.2. Arctic environment issues

As mentioned above, we expect to see the smallest differences between in situ data and model estimates in the simplest situations, that is, in days of clear skies over open waters. When situations get more complicated, more differences may emerge from different ways of modeling the environment. The accuracy of a satellite PAR product, here obtained from the comparison with in situ values, can be evaluated by examining the specific environmental factors. The most important ones for light propagation in the Arctic are persistent low solar elevation, changing surface albedo due to sea ice, and high cloudiness. This section examines the residuals between satellite-derived and in situ daily PAR as a function of local solar noon (minimum daily SZA), the effects of the clouds and surface albedo (Fig. 10; Table 3).

5.2.1. Sun elevation

We found a weak significant negative relationship between the SZA at noon time and the PAR error for the LUT method (Table 3). When SZA at noon was >80°, the LUT-based method almost systematically underestimated daily PAR. First, this result may be explained by the fact that the lower the sun rises above the horizon, the more energy comes from diffuse relative to direct irradiance, increasing the importance of accurate aerosol and water vapor estimation, which are considered constant. Second, high SZAs invalidate the plane-parallel assumption used in the SBDART radiative transfer model. As a result, PAR tends to be underestimated during days with dimmed light from below the horizon. A spherical geometry in radiative transfer model (Sobolev, 1975; Lenoble, 1985; Dahlback & Stamnes, 1991; Thomas & Stamnes, 1999; Spurr et al., 2007) may be used to properly estimate the effects of the clouds and surface albedo (Fig. 10; Table 3).

5.2.2. Surface albedo

An earlier version of the Ed LUT used a constant surface albedo (0.06 for clear water), independent of the amount of ice cover. A fairly strong negative relationship between the relative error of the estimates and the increase in SIC was found, suggesting an increase in PAR underestimation (negative slope) when SIC was increasing (Laliberté & Belanger, 2014). This was explained by the fact that the presence of SIC in a pixel increases the surface albedo, which amplifies the surface irradiance by multiple scattering between the surface and the overlying atmosphere (Gardiner, 1987). Following this, a sensitivity analysis of the surface albedo was performed through radiative transfer simulations. An example is shown for the 29th of April 1998 (Fig. 11) when the ship was in the completely ice covered sector of the Baffin Bay (74.7° W, 76.3° N). Assuming a typical surface albedo for an open ocean surface (0.06), a daily PAR underestimation of 30% was obtained. A very good PAR estimation (underestimation of 3%) was obtained when coupling open waters \( A_s \) with the modeled surface albedo using SIC (Eq. (2)).

The inclusion of the \( A_s \) as an input parameter to our Ed LUT strongly reduced the linear negative relationship previously found between SIC and the PAR residual (for \( A_s, \rho < 0.1, R^2 = 0.02 \), but increased the RMSE of PAR estimation under open water conditions (+5%) (Tables 2 and 3; Fig. 10b). This may be attributed to a combination of factors like the overestimation of sea albedo or inexact assumption on aerosols type and load (or due to ship displacement, see Section 4.1). The OBPG algorithm determines \( A_s \) with aerosols and solar zenithal angle, therefore not varying wind, sea ice, white caps, or diffuse water reflectance. The algorithm discards icy areas (i.e., SIC >10%) because they would be interpreted as cloudy in the PAR algorithm. Alternatively, if OBPG could process their PAR product in spite of surface conditions, the OBPG PAR database would be much more complete, increasing the

![Fig. 6. Scatter plot of in situ daily PAR versus satellite-derived daily PAR using the OBPG method. The dot color corresponds to the CV intraday and the inset is a cumulative frequency distribution of the number of matchups as a function of CV intraday threshold.](image)

![Fig. 7. Scatter plot of daily PAR derived using LUT and OBPG methods inside a 280 km ISCCP pixel. Each point represents the PAR average for one day of the month of July 2004. The error bars represent the standard deviation calculated using the 580 4.6 km pixels within the 280 km ISCCP pixel. The 4 points outside the 30% dashed lines are cases where LUT method yields higher PAR values than the OBPG method.](image)
Fig. 8. a) Averaged daily PAR computed using available daily PAR from OBPG for year 2004; b) number of days with OBPG daily PAR available; c) evolution of the differences in daily PAR between methods (OBPG - LUT) with a loess (locally weighted regression) smoothing function applied (blue line with its standard deviation in gray); d) frequency distribution of daily PAR for both methods; e) map depicting average difference in daily PAR between methods (OBPG - LUT); and f) histogram of all the differences.

Fig. 9. Sum of the daily PAR (Em⁻² d⁻¹) for the 2004 PAR from OBPG(left) and LUT(right).
respectively. SZA is shown as open gray circles. Simulations were made from 8 daily CF, illustrated in the Fig. 10c, the effect of clouds is not related to PAR resid-
uals (solar noon, b) surface albedo and c) the cloudiness, here defined as the product of CF and $T_s$.

5.2.3. Cloudiness

Cloudy sky conditions dominate over the Arctic ocean (Eastman & Warren, 2010). The effect of clouds is parameterized as the products of fractional cloud cover and cloud optical thickness, that is $CF \times T_{cl}$. As illustrated in the Fig. 10c, the effect of clouds is not related to PAR residuals ($p = 0.98$; Table 3). This means estimates under an overcast sky may be subject to the same error as estimates under clear sky. Small fluctuations decreasing or increasing the effect of clouds, like sunbreaks or isolated clouds, are equally under-represented at the coarse ISCCP pixel resolution. Transmission through broken clouds or multiple cloud layers affects the PAR amplitude, spectral shape, and diffuse-to-
direct ratio and is highly position-dependent. While difficult to quantify, these cloud effects surely increase the inherent uncertainty associated with the LUT method.

By using coarse ISCCP input for clouds, the LUT method does not pre-
cisely account for transitions in the cloud conditions. Part of a pixel area may be covered with thick clouds and the other part may be under clear sky conditions, but anywhere in the pixel is a gradient between the local conditions and the one found with the surrounding pixels, causing the PAR values to be averaged on relatively large scales. This alters PAR ac-
curay as soon as the estimate is spatially close to abruptly changing conditions, like passing from a clear sky to an overcast sky. Moreover, the method does not precisely distinguish between configurations of the ice-cloud and water-cloud conditions within the pixel. The presence of sea ice under cloudy conditions have a strong impact on the PAR.

Ignoring the interaction aspect may lead to significant estimation error on regional scales. Therefore, as soon as the environmental condi-
tions are distributed heterogeneously within the pixel, there will be an error on a local estimation. Nonetheless, this effect should fade when large scales are considered.

Chernokulsky and Mokhov (2012) showed that the ISCCP total cloud cover variability over the Arctic was lower than that observed in situ or by other satellites and reanalysis. In addition, they showed that the ISCCP cloudiness was underestimated in summer. This may explain why the LUT method yields higher PAR values when compared to in situ measurements (Fig. 4) or to OBPG estimates in May (Fig. 8c).

The OBPG algorithm estimates daily PAR from a single satellite pass, but several passes are available at high latitudes providing multiple daily PAR estimates for a single pixel. The representation of diurnal variability in cloud cover is limited to the number of valid scenes imaged by the sensor. Theoretically, the OBPG products could be more precise in the Arctic since more satellite passes are available for a given region, contributing to the daily average. Binning of multiple satellites (using a weighted mean with respect to SZA) helps to overcome the assump-
tion of a stable cloud-surface system, thus addressing the largest accepted drawback of the OBPG method.

Note that the conversion to flux would be improved if a more accu-
rate (or more representative of Arctic conditions) cloud bidirectional ef-
fact was considered (Macke, Dlhopolsky, Mueller, Stuhlmann, & Raschke, 1995). Overall, the method accounts for important parameters (solar elevation and cloud-surface albedo) but lacks precision to esti-
mate cloud-surface albedo, which may lead to increased errors in an Arctic environment where in the summertime, cloud cover usually oc-
cupies 80% to 90% of the sky (Vavrus & Waliser, 2008; Warren, Hahn, London, Chervin, & Jenne, 1988; Rossow & Schiffer, 1991).

6. Conclusion and perspectives

Our evaluation showed that the LUT method is characterized by an uncer-
tainty of 33% compared to 20% for the OBPG method. This is mainly due to difference in spatial and temporal resolution of inputs used to inter-
polate the LUT. The former method will always represent bulk PAR values for a large region, while the latter will be more appropriate for fine-scale features. Since the mean values of the PAR distributions are quite similar in both cases, the LUT method, when fed with low resolution ISCCP inputs, is more appropriate for large-scale studies mostly because it covers pixels with ice and periods of low sun elevation.

The very high temporal resolution of ISCCP input (3 h) did not fully compensate for its low spatial resolution (280 km). In addition, cloud fraction alone over the ocean is only accurate to 15–25% in polar regions during summer (Rossow & Garder, 1993). Radiative transfer calculations have an uncertainty of 3% even when atmospheric properties are known a priori (Ricchiazzi et al., 1998). Nevertheless, the performance of the LUT method may be considerably improved if cloud and atmospheric in-
formation with better spatial resolution is used as input. For example, cloud optical thickness and cloud fraction are already derived from ocean color sensors such as MODIS and MERIS (and soon from European Agency’s Ocean and Land Colour Imager (OLCI) onboard Sentinel-3 satellites). Adding new dimensions to the LUT for aerosol and water vapor, also derived from ocean color sensors, could further improve the method.

![Fig. 10. Scatter plot of residuals between LUT estimates and in situ data as a function of (a) solar noon, (b) surface albedo and (c) the cloudiness, here defined as the product of CF and $T_s$.](image)

![Fig. 11. Sensitivity analysis of surface albedo performed using SBDART. Open black circles are in situ instant PAR observations onboard the CCG Pierre Radisson during the NOW project, gray and black lines are SBDART simulations using $A_s = 0.06$ and 0.95, respectively. SZA is shown as open gray circles. Simulations were made from 8 daily CF, $T_{cl}$ and $O_3$ (ISCCP).](image)

<table>
<thead>
<tr>
<th>Solar noon (LUT)</th>
<th>Solar noon (OBPG)</th>
<th>Cloud effect</th>
<th>Surface albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = -1.16x + 84.73$</td>
<td>$y = 0.3x - 9.61$</td>
<td>$y = 0.01x + 6.92$</td>
<td>$y = 26.55x + 4.66$</td>
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<tr>
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<td>$R^2 = 0.02$</td>
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<td>$R^2 = 0.02$</td>
</tr>
<tr>
<td>$p = 0.001$</td>
<td>$p = 0.049$</td>
<td>$p = 0.98$</td>
<td>$p = 0.1$</td>
</tr>
</tbody>
</table>
The LUT method was initially conceived to include spectral UV-B and UV-A for water column photochemical modeling purposes. A preliminary validation using GUV-510 measurements at 313 nm (Xie et al., 2012) show similar model performance in the UVB. In addition, LUTs for under water spectral irradiance (i.e., E_u(0, −1)) taking into account direct and diffuse irradiance specular reflectance are already implemented and could be made available to the community. 

Open waters within the central Arctic ice pack are frequent in summer. Given that light is available, primary productivity (PP) may be significant in these waters if phytoplankton have access to nutrients. Thus, for PP modeling, PAR estimation is relevant in all sea ice conditions. A step forward for future applications and a significant improvement of the LUT method would be to assume a transmission function for ice cover and subsequently be able to estimate PAR in the water column under sea ice. Light transmission model through sea ice and meltponds are now becoming available and used to assess under-ice primary production (Arndt & Nicolaus, 2014; Fernández-Méndez et al., 2015).

Adding an ice component to the model would produce a complete and relevant estimation of the irradiance reaching the water over the whole Arctic ocean, especially useful to study phytoplankton spring bloom and in-ice or under-ice photochemical processes. Despite a relatively good precision, the NASA OBPG L3 PAR product should be used with caution at high latitudes because it is limited to open waters and do not provide estimates during the period of the year when the sun is just above the horizon (e.g., Fig. 9). Extending the OBPG’s energy budget approach over ice is feasible, but would require estimating surface albedo and light absorbed within the ice pack, which is difficult in the presence of clouds, or when the pixel is partially covered with ice. However, the method is more accurate, at least in principle, to estimate PAR just below the ocean surface (the surface albedo term disappears in Eq. (3)), offering the possibility to obtain useful estimates of PAR just below sea ice when information about PAR absorption within the snow/ice cover is available.

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