A whale of an opportunity: Examining the vertical structure of chlorophyll-a in high Arctic waters using instrumented marine predators

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Abstract
Sixty hours of direct measurements of fluorescence were collected from six bowhead whales (Balaena mysticetus) instrumented with fluorometers in Greenland in April 2005 and 2006. The data were used to (1) characterize the three-dimensional spatial pattern of chlorophyll-a (Chl-a) in the water column, (2) to examine the relationships between whale foraging areas and productive zones, and (3) to examine the correlation between whale-derived in situ values of Chl-a and those from concurrent satellite images using the NASA MODIS (Moderate Resolution Imaging Spectroradiometer) EOS-AQUA satellite (MOD21, SeaWifs analogue OC3M and SST MOD37). Bowhead whales traversed 1600 km², providing information on diving, Chl-a structure and temperature profiles to depths below 200 m. Feeding dives frequently passed through surface waters (>50 m) and targeted depths close to the bottom, and whales did not always target patches of high concentrations of Chl-a in the upper 50 m. Five satellite images were available within the periods whales carried fluorometers. Whales traversed 91 pixels collecting on average 761 s (SD 826) of Chl-a samples per pixel (0-136 m). The depth of the Chl-a maximum ranged widely, from 1 to 66 m. Estimates of Chl-a made from the water-leaving radiance measurements using the OC3M algorithm were highly skewed with most samples estimated as <1 mg m⁻³ Chl-a, while data collected from whales had a broad distribution with Chl-a reaching >9 mg m⁻³. The correlation between the satellite-derived and whale-derived Chl-a maxima was poor, a linear fit explained only 10% of the variance.

Key words: Bowhead whale, chlorophyll-a, fluorometer, MODIS, remote sensing

Introduction
The spring phytoplankton bloom constitutes the single most important biological event in the marine Arctic ecosystem, with cascading impacts that reach the top of the food chain (Arrigo & Van Dijken 2003; Heide-Jørgensen & Laidre 2004). With the advent of advanced ocean colour satellite instruments, there has been an explosion of the use of these data to estimate biological, biogeochemical, and physical parameters such as the surface concentration of chlorophyll-a (Chl-a) (Carder et al. 1999; Sathyendranath 2000; Miroslaw & Stramski 2004; Heide-Jørgensen et al. 2007a). This is especially true in remote localities such as polar environments, where year-round observations are difficult, effort is low, and ice-associated primary production often cannot be monitored with traditional methods (Dierssen & Smith 2000; Burenkov et al. 2001). While space-based remote sensing techniques allow for the characterization of regional dynamics of phytoplankton abundance over broad scales of space and time by relying on measurements of water-leaving radiance (estimating Chl-a as the total return of reflectance through the optical depth of the water
column) (Morel & Maritorena 2001; Clarke et al. 2006), little insight is gained concerning the three-dimensional dynamics of the environment and vertical structure of Chl-a in the water column.

Disko Bay, located between sub-Arctic waters of southwest Greenland and the high Arctic waters of Baffin Bay, is among the most productive springtime coastal sites in West Greenland (Levinsen et al. 2000; Madsen et al. 2001, 2008a, 2008b; Heide-Jørgensen & Laidre 2004; Heide-Jørgensen et al. 2007a) (Figure 1). During winter, the water column is well mixed and the lack of light and the seasonal ice coverage inhibits net growth of phytoplankton. After sea ice break-up solar radiation and melt water warm and dilute the surface layer, trapping nutrients in a stable surface layer that stimulates the phytoplankton bloom. When initiated, the exponential growth of phytoplankton quickly depletes the surface layer of nutrients (Nielsen & Hansen 1995, 1999; Pedersen et al. 2006) and after the bloom sediments to the bottom.

An aggregation of approximately 1200 bowhead whales (*Balaena mysticetus* Linnaeus, 1758) that are

![Figure 1. Study area in West Greenland together with bathymetric structure of the sea floor in Disko Bay. All data were collected near the town of Qeqertarsuaq <70 km from the coastline.](image)
part of a population extending between eastern Canada and West Greenland (Heide-Jørgensen et al. 2007b) arrive in Disko Bay in February and remain in the area until May, where they feed intensively on secondary producers (i.e. amphipods and copepods Calanus glacialis, C. hyperboreus, and C. finmarchicus). These whales traverse optically complex coastal waters at the peak primary production bloom in the Arctic and tagging methods are well developed (i.e. Heide-Jørgensen et al. 2003, 2006; Laidre et al. 2007). Therefore they offer an ideal opportunity to serve as oceanographic sampling platforms in high-latitude waters.

In this study, we instrumented bowhead whales with fluorometers (archival dive–temperature–fluorescence) to sample the water column in Disko Bay. These data were used to (1) examine bowhead whale diving patterns relative to the patterns of Chl-a and temperature in the Disko Bay water column in spring, and (2) derive and interpolate in situ water column fluorescence estimates of Chl-a corresponding to a satellite-derived surface transect of the whales’ movement. We present a description of the spatial variation in the vertical structure of Chl-a in Disko Bay along with corresponding estimates of Chl-a derived from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite-derived global algorithm and variation in wavelength specific band ratios. This study demonstrates the utility of marine top predators as autonomous physical and biological samplers for extending the interpretation of remotely sensed data into the vertical structure of the water column. This is particularly useful in the high-latitude polar ecosystem, where seasonally ice-covered waters limit ship access to open water periods and make logistics difficult and costly.

Materials and methods

**Bowhead whale instrumentation and data collection**

Bowhead whales were instrumented with WetLabs (Corvallis, Oregon) fluorometers (Fluorescence Nephelometric Turbidity Unit, FLNTUB) in Disko Bay, West Greenland in April 2005 and 2006 (Figure 1). Fluorometers were mounted on a cylindrical float (28 x 8 cm) which included a VHF transmitter (Telonics, Mesa, Arizona) and an ARGOS satellite-linked tag (Wildlife Computers SPOT4, Redmond, Washington) for instrument recovery (Figure 2). Floats were attached to the whales using stainless steel harpoon tips (25 x 100 mm). All tags were deployed using an 8-m long fiberglass pole from a small open boat approximately 4–5 m away from the whale (cf. Heide-Jørgensen et al. 2003, 2006). During pursuit, the float tags were held in a PVC housing mounted to the pole. Once the harpoon tip was imbedded in the blubber of the whale, the float was released from the housing. The float was tethered to a 1.5-m long stainless steel wire with a corrosive magnesium bolt which released the float from the whale after a set period of time (generally 3–4 days; however, some floats stayed on longer). Floats were recovered using real-time ARGOS satellite locations (Harris et al. 1990) and a fine-scale VHF search conducted using directional antennas mounted on a 50-foot boat (r/v Porsild, Arctic station, Copenhagen University) or from a small boat. The FLNTUBs sampled fluorescence, pressure (resolution 1 m), and temperature (resolution 0.001°C) every second at a resolution of 1 m.

After tags were retrieved, data were downloaded to a PC for processing and analysis. Voltage readings from the FLNTUBs were downloaded and converted to Chl-a using standard equations developed by WetLabs (ECOView software). These Chl-a values were calibrated against in situ Chl-a measurements from the waters of Disko Bay (see Heide-Jørgensen et al. 2007). All samples where depth was 0 m were removed from the data sets together with values of Chl-a that were less than or equal to 0 mg m⁻³. Satellite positions were received when the whales surfaced to breathe; and a linear interpolation between each known whale location was used to create a simulated whale location every second through horizontal x-y space for the entire tracking period. ARGOS location qualities of LC-0 or better were flagged and used as good quality. We assumed a constant swim speed during the period of time the tag was on the whale, a reasonable assumption based...
on behavioural data collected from bowheads in the past (Heide-Jørgensen et al. 2003).

Chl-a profiles were created using the ‘griddata’ function in MathWorks MATLAB software. The interpolated length scale (cell size) was determined based on visual inspection of the dive track and total distance traversed by the whale. The distance between each surface interval (i.e. ARGOS position received when the whale surfaced to breathe) was used as the basis for the horizontal cell size and vertical cell size was 1 m (same as that of the pressure transducer). A linear interpolation method was used to estimate the Chl-a of each cell based on a Delaunay triangulation.

Satellite data product

Data were obtained from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS: EOS AQUA satellite). Daily data products used included Chl-a (MOD21, SeaWiFs analogue OC3M) and 4 µm sea-surface temperature (MOD37, SST). These atmospherically corrected and georegistered products have a spatial resolution of 1 km (Gordon & Wang 1994; O’Reilly et al. 2000; Martin 2004).

The data work flow included the use of Windows Image Manager WimSoft® for importing and spatial sub-setting of MODIS data prior to construction of a geodatabase in the ESRI ArcGIS® grid format. Cell values were extracted from each image corresponding to the same day and location as the in situ Chl-a sampled from the bowhead whales. Thus, in situ measurements of Chl-a concentration were spatially comparable with daily remotely-sensed estimates of water-leaving radiance and Chl-a for all cloud-free days.

Spatial and statistical analysis

All pixels within each daily MODIS image were assigned a unique cell ID value. Geographic positions along the whale track together with associated Chl-a, temperature, and band ratios were associated to MODIS Chl-a and temperature values in each individual cell using ArcGIS 9 (Hawth’s Tools extension, www.spatial ecology.com). Summary statistics of whale fluorometric data were obtained in each pixel. The pixel was considered to be the smallest sampling unit and standardized the analysis. We calculated whale-derived (WD) Chl-a maximum in each pixel (from the fluorometer), associated depth and temperature, and mean WD Chl-a through all depths. Pixel-based summaries of data collected from instrumented whales were correlated with summaries of satellite-derived (SD) Chl-a data in each pixel. The distribution of Chl-a values along the whales’ trackline was characterized by both mean and maximum WD Chl-a. WD sea temperatures at 1 and 2 m depths were correlated to satellite-derived SST. Statistics used included linear models, KS-tests, and ANOVAs using $p < 0.05$ as the level of significance.

Results

Bowhead whale data

Six bowhead whales were instrumented with fluorometers in April 2005 ($n = 5$) and 2006 ($n = 1$) along the south coast of Disko Island (Figure 1, Table I). Dates of deployment spanned 22 April to 1 May (Laidre et al. 2007). Approximately 60 h of measurements (every second) were collected from the whales. Spatial coverage of Disko Bay was focused between the coastline and 50 km offshore. Whales did not range farther than 100 km off the coast while instrumented. Whales travelled in a number of different vectors from their tagging sites and covered approximately 200 km (straight line distance) along the south coast of Disko Island (Figure 3).

Diving behaviour was variable, with mean dive depths ranging between 53 m (SD 35) and 94 m (SD 124). The maximum depth reached by an instrumented whale was 380 m (whale 02-05), which was deeper than maximum depths for other whales (ranging between 110 and 234 m). Most whales’ dives were focused in the upper 200 m of the water column, with surfacing intervals 7–9 min apart. Mean dive durations ranged from 3 min (SD 2) to 13 min (SD 11) and the maximum dive duration in this study was 41 min. In general, whales spent the largest proportion of their time in the

<table>
<thead>
<tr>
<th>Whale ID</th>
<th>Date deployed</th>
<th>Time deployed</th>
<th>Deployment duration</th>
<th>Sex and size of whale</th>
<th>Chl-a max (SD) (mg m$^{-3}$)</th>
<th>Depth at Chl-a max (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01-05</td>
<td>22/4/05</td>
<td>13:56</td>
<td>6 h, 44 min</td>
<td>M, 15-18 m</td>
<td>4.63 (0.69)</td>
<td>12</td>
</tr>
<tr>
<td>02-05</td>
<td>26/4/05</td>
<td>17:12</td>
<td>8 h, 15 min</td>
<td>F, 15-18 m</td>
<td>21.22 (2.49)</td>
<td>5</td>
</tr>
<tr>
<td>03-05</td>
<td>28/4/05</td>
<td>15:30</td>
<td>5 h, 28 min</td>
<td>U, 15-18 m</td>
<td>7.84 (2.22)</td>
<td>8</td>
</tr>
<tr>
<td>04-05</td>
<td>3/5/05</td>
<td>11:30</td>
<td>13 h, 50 min</td>
<td>F, 12-15 m</td>
<td>6.12 (1.60)</td>
<td>8</td>
</tr>
<tr>
<td>05-05</td>
<td>1/5/05</td>
<td>18:11</td>
<td>7 h, 57 min</td>
<td>F, 12-15 m</td>
<td>6.06 (1.22)</td>
<td>6</td>
</tr>
<tr>
<td>01-06</td>
<td>1/5/06</td>
<td>18:55</td>
<td>17 h, 5 min</td>
<td>U, 15 m</td>
<td>2.87 (0.22)</td>
<td>13</td>
</tr>
</tbody>
</table>
upper 10 m of the water column (Table II) due to surfacing behaviour. Dives did not always target the most productive strata of the water column (as indicated by the patches of high Chl-a) and instead whales frequently dove to the bottom, where Chl-a levels were low. The dive profiles did, however, allow

**Table II.** Fraction of time spent in 10-m bins of the water column (between 0 and 100 m) for each instrumented whale. Time spent at 0 m (when the whale was at the surface and the fluorometer was exposed to air) was not included in the analysis, thus fractions are representative of the sub-surface use of the water column.

<table>
<thead>
<tr>
<th>Whale ID</th>
<th>01-05</th>
<th>02-05</th>
<th>03-05</th>
<th>04-05</th>
<th>05-05</th>
<th>01-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 m</td>
<td>0.44</td>
<td>0.32</td>
<td>0.12</td>
<td>0.20</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
<td>11-20 m</td>
<td>0.30</td>
<td>0.28</td>
<td>0.06</td>
<td>0.11</td>
<td>0.17</td>
<td>0.05</td>
</tr>
<tr>
<td>21-30 m</td>
<td>0.09</td>
<td>0.13</td>
<td>0.08</td>
<td>0.09</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td>31-40 m</td>
<td>0.04</td>
<td>0.13</td>
<td>0.15</td>
<td>0.10</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>41-50 m</td>
<td>0.01</td>
<td>0.05</td>
<td>0.20</td>
<td>0.10</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>51-60 m</td>
<td>0.01</td>
<td>0.03</td>
<td>0.15</td>
<td>0.14</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>61-70 m</td>
<td>0.01</td>
<td>0.01</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>71-80 m</td>
<td>0.01</td>
<td>0.01</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.15</td>
</tr>
<tr>
<td>81-90 m</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>91-100 m</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>&gt;100 m</td>
<td>0.07</td>
<td>0.04</td>
<td>0</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>
for a robust characterization of the Chl-a and temperature composition in the waters traversed by the whales from the surface down to at least 200 m.

In 2005, 42.5 h of Chl-a and temperature data were collected from whale tags at depths between 0 and 380 m. In 2006, 0.6 h were sampled between depths of 0 and 111 m. WD Chl-a values ranged between 0.01 and 33 mg m\(^{-3}\) (Figure 4a-f) and all whales dove well beneath the optical depth used for satellite-based observations. The establishment,

Figure 4a-f. Chl-a and depth profiles from six whales instrumented in Disko Bay, West Greenland in April and May 2005 and 2006. Note the succession of the phytoplankton bloom is apparent.
build-up and sedimentation of the phytoplankton bloom over a 1.5-week period can be seen from the series of WD Chl-a values between 22 April and early May. Values increased from 5 to 35 mg m\(^{-3}\), one order or magnitude in one week (Figure 4a-f). The overall succession and depth distribution of the phytoplankton recorded by the whale tags is comparable to the Chl-a depth profiles recorded simultaneously at a permanent sampling station 1 km south of Qeqertarsuaq (Madsen et al. 2008b). Mean values of WD Chl-a, when binned by 1 m increments, ranged between 2.9 (SD 0.2) mg m\(^{-3}\) and 21.2 (SD 2.5) mg m\(^{-3}\). Temperatures were negative throughout the first 80–100 m below the surface and increased to positive values below 100 m. Interpolation of WD Chl-a demonstrated horizontally patchy and variable Chl-a concentrations along each whale’s trackline. WD Chl-a maximum values occurred at a wide range of depths, between 1 and 66 m (Table I).

**Satellite data**

Five MODIS images were available within the time periods the whales carried fluorometers in Disko Bay. Tagged whales traversed a total of 91 individual pixels where estimates of Chl-a and water-leaving radiance by wavelength were available. The number of pixels in each MODIS image that spatially coincided with whale movements ranged from 5 to 44 (mean 18, SD 16). In each pixel, on average, 761 (SD 826) measurements were sampled by whales at a range of depths (1–136 m). The WD Chl-a maximum in each pixel ranged widely (0.9 – 12.7 mg m\(^{-3}\)) and occurred over a range of depths (1 and 66 m). Of the Chl-a maxima obtained in each pixel, 71% occurred at depths above 10 m, 20% occurred at depths between 11 and 30 m, and 1% occurred below 30 m. The temperature value at the WD Chl-a maximum ranged from -0.5 to -1.6°C.

**Comparison between data sets for Chl-a**

Interpolation of Chl-a along whale tracklines demonstrated considerable variability in the depth and extent of Chl-a patches (Figure 5). This was apparent in all profiles created from instrumented whales. Large patches of high concentration of Chl-a were detected at a range of depths down to about 50 m. The correlation of these data with corresponding pixel values (Figure 5, top row of boxes) estimated by the MODIS OC3M algorithm was poor and not significant. Low values of SD Chl-a were found along all whale tracklines, and when SD values were high, they infrequently corresponded with high levels of WD Chl-a, even at depths >10 m. The correlation between the MODIS OC3M algorithm Chl-a values and WD Chl-a max was also poor. A linear fit to the data explained 10% of the variance and MODIS estimated on the order of 30% of the Chl-a in the water column (\(y = 0.3x + 6.2, R^2 = 0.11\)).

The frequency distribution of WD and SD Chl-a values in each of the 91 pixels was significantly different (\(p < 0.05\)) (Figure 6). The distribution of values obtained from the MODIS OC3M algorithm (mean 1.9 mg m\(^{-3}\), SD 3.4) was highly skewed to the left with most values estimated as <1 mg m\(^{-3}\).
Low Chl-a concentrations were often predicted by the satellite (range $0.2 - 22.3 \text{mg m}^{-3}$). Conversely, both the mean WD Chl-a (mean $3.6 \text{mg m}^{-3}$, SD 1.7, range $0.6 - 7.9$) and maximum WD Chl-a (mean $6.7 \text{mg m}^{-3}$, SD 3.0, range $0.9 - 12.7$) had broad distributions with ranges outside of those suggested by SD measurements (Figure 6). There was no obvious Chl-a peak within either WD mean or WD maximum Chl-a distribution. With the exception of extremely low values, the WD mean distribution was in slightly better agreement with the satellite estimates (Figure 6). The interpolated profile of whale WD temperature suggests that the warmer temperatures at deeper depths ($+9^\circ C$, part of the West Greenland current) could be detected beyond depths of 100 m (Figure 7). The linear correlation between WD SST (1 m depth) and MODIS SST was good (Figure 8); however, WD values were almost 60% below those estimated by MODIS ($y = 0.58x - 0.61$, $R^2 = 0.30$).

**Discussion**

Previous studies on the foraging behaviour of bowhead whales in Disko Bay have documented high variability in depths of foraging dives (Laidre et al. 2007), with whales apparently foraging between 80 and 200 m. In early spring feeding studies, these dives frequently corresponded to depths close to the complex bottom topography along the slope of Disko Bay. This may be due to bowhead whales in Disko Bay targeting pre-ascension stage copepods, which occur in high density patches near the bottom in early spring (Madsen et al. 2001).

In this study, bowhead whale dives did not always target the most productive areas of the water column, as measured by the relationship between terminal depth and high concentrations of Chl-a. Instead, and contrary to our expectation, whales often traversed these productive areas and dives terminated in areas with relatively low Chl-a concentrations when compared to the upper 50 m of the water column. The upper 50 m is known to be an important area for copepods, which ascend from depth in spring and feed on the phytoplankton (Chl-a) at the surface. However, in the case of bowhead whales in Disko Bay, it may be energetically more efficient to search for high density copepod patches near the bottom before they ascend (Laidre et al. 2007). Thus the primary production levels in the upper 50 m may not have much influence on where whales spend their time, at least in early spring before the copepod ascension. It is possible that after
copepods ascend, the whales’ strategy changes and they target surface waters and have a closer association with high levels of Chl-a. We infer that whales forage at the terminal points of their dives, although obtaining specific data to demonstrate that this is the case is difficult.

The synoptic spatially continuous portal of ocean primary production supplied by satellite-based ocean colour instruments offers coverage that is impossible to achieve with traditional ship-based or moored instrumentation. These techniques allow for the characterization of regional dynamics of phytoplankton abundance over broad scales of space and time, especially in remote areas where there is considerable interest in mapping and monitoring changes. However, given that water-leaving radiance measurements only estimate Chl-a as the total return of reflectance through the optical depth of the water column (Morel & Maritorena 2001; Clarke et al. 2006), little insight is gained concerning the three-dimensional structure of Chl-a, especially below the optical depth.

Several studies have demonstrated the utility of marine mammals as adaptive samplers for areas of high oceanographic interest (Boehlert et al. 2001; Boyd et al. 2001; Lydersen et al. 2002; Biuw et al. 2007; Boehme et al. 2008a, 2008b; Charrassin et al. 2008; Costa et al. 2008; Teo et al. 2009), and this study expands on previous work by integrating and comparing autonomous in situ sampling with satellite-based observations. Few in situ studies are available to corroborate satellite-derived coastal measurements of production in the Arctic, where storms, variable wind-induced mixing, and coastal upwelling increase the complexity of in-water optical properties. The instrumentation of bowhead whales to concurrently sample the Arctic environment provided a useful comparison to the global satellite data algorithms frequently used in high-latitude waters. At the same time, this approach offered previously unobtainable three-dimensional data along unique transects on coastal Chl-a structure in Disko Bay.

The MODIS OC3M satellite-derived Chl-a estimates correlated poorly to in situ WD Chl-a values and estimated < 30% of the actual Chl-a in the water. This algorithm measured low concentrations of Chl-a despite much higher Chl-a levels in the water column even at shallow depths (Figures 5 and 6). This finding was not surprising given similar poor results in other polar seas (Dierssen & Smith 2000; Burkenov et al. 2001). Global calibrations of geophysical algorithms tend to be poorly correlated with actual values at high latitudes (Bailey & Werdel 2006; Heide-Jørgensen et al. 2007) despite proving robust in more temperate waters (Gohin et al. 2008). Global algorithms are designed for less optically complex open ocean environments (Carder et al. 1999; Sathyendranath 2000; Miroslaw & Stramski 2004; Heide-Jørgensen et al. 2007). The coastal waters of the high Arctic experience rapid changes in phytoplankton abundance and concentration of dissolved organic matter, and it is highly unlikely that the spatial and temporal progression of these variables is correctly captured by satellite observations.

It is important to note that not all potential maximum depths in a given pixel were sampled by diving whales. Thus the whale-derived Chl-a maximum is indicative of the potential maximum value of Chl-a at a given location, not the absolute maximum. Regardless, the WD Chl-a measurements revealed far more structure below the water surface and higher Chl-a concentrations than reported based on satellite data. Furthermore, the spatial precision of the analysis was limited by the degree of error around the good-quality Argos locations. In the future, similar studies using cetaceans would benefit from the GPS technologies presently being developed and tested for marine mammals.

The use of both in situ fluorometers and satellite water-leaving radiance algorithms for estimating Chl-a involve the fluorescence and absorption of photons of light by phytoplankton. These measurable processes vary predictably with the concentration of Chl-a. However, the mechanisms behind the derivation of Chl-a estimates differ methodologically. Satellite-based water-leaving radiance algorithms use the signal at two or more bands in the electromagnetic spectrum of light. The higher the Chl-a concentration the more light is absorbed, and therefore the less light is received at the satellite sensor. Conversely, fluorometers deployed in the water column rely upon the fluorescence properties of Chl-a absorbing a photon at shortwave high-energy light and then re-emitting it at a longer wavelength of light with lower energy to provide an in situ estimate of concentration of phytoplankton cells.
The data collected from instrumented whales are based solely on an artificial source of light and are thus useful in characterizing properties of the water which are independent of the environmental setting in which it is found. Conversely, the data collected by the satellite are based on solar or natural light as well as backscattering through the atmosphere and water column, and document the cumulative effects of numerous interactions with the environment. This distinction recognizes that optical properties through the depth of the water column are structurally complex. When limited to two-dimensional surface observations, the interpretation of structure often fails.

Satellite-based observations from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS: EOS AQUA) satellite capture the spatial variability of the normalized water-leaving radiance at a single time stamp over a broad spatial extent (resolution of 1 km). Bowhead whales equipped with fluorometers in coastal waters travel continuously in space and time and dive every 5–7 min. Each approach offers a unique perspective of characterizing the spatial and temporal variation of the three-dimensional dynamics of the marine environment.

Top predators offer a platform for sampling the marine environment in areas that cannot be adequately or reliably obtained with standard sampling techniques (Reid & Croxall 2000; Boyd & Murray 2001; Charrassin et al. 2002, 2004; Fraser & Hoffmann 2003; Nicholls et al. 2008). Consequently, biological autonomous sampling systems have immense potential to contribute to oceanographic and satellite-based data in a cost-effective manner (Boehlert et al. 2001; Boyd et al. 2001; Lydersen et al. 2002, 2004; Biuw et al. 2007; Boeume et al. 2008a, 2008b; Charrassin et al. 2008; Costa et al. 2008). In this paper we also examined whether marine predators could be used to collect and provide robust data to examine the spatial distribution of chlorophyll-a in the high Arctic. This was combined with optical properties of water-leaving radiances from space-based observations and used to extend the three-dimensional picture of primary production in a coastal zone. This study demonstrates that both the estimates of Chl-a derived by global ocean colour algorithms as well as the spatial variation of those estimates relative to in situ fluorescence measurements are not well correlated. Thus, innovative methods for collecting detailed in situ data are necessary for both calibrating and validating data collected from satellites.

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