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Analysis of Optical Spikes Reveals Dynamics of Aggregates in the Twilight Zone

Nathan Briggs

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ANALYSIS OF OPTICAL SPIKES REVEALS DYNAMICS OF
AGGREGATES IN THE TWILIGHT ZONE

By

Nathan Briggs
B.A. Williams College, MA, 2003

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Advisory Committee:

Mary Jane Perry, Professor of Marine Sciences, Advisor
Huijie Xue, Professor of Marine Sciences
Eric D’Asaro, Professor of Oceanography, University of Washington
Craig Lee, Professor of Oceanography, University of Washington
The “biological pump,” whereby phytoplankton grow in the surface ocean, aggregate, and sink, is a critical process contributing to global atmospheric CO₂ drawdown and provides the vast majority of food for deep ocean and benthic ecosystems. The strength of this pump hinges on the amount of material that stick together to form larger aggregates, the sinking rates of these aggregates, and the rate at which they are consumed as they sink. However, marine aggregates, also called “marine snow,” are often fragile and notoriously difficult to sample, their sinking rates are highly variable and difficult to quantify, and their concentrations can vary greatly over short periods of time and space during a phytoplankton bloom. Here we present a method for addressing some of these problems and through the analysis of “spikes” that aggregates cause in the signals of low-power optical instruments. As part of the North Atlantic Bloom 2008 project, optical backscatter, attenuation, and fluorescence data were measured on four Seagliders and four cruises south of Iceland for three months beginning April 2008. Ships and gliders followed a Lagrangian mixed-layer float that tracked a single patch of water.
We first compare the timing and density of spikes recorded on different optical instruments aboard gliders and ships and find strong agreement in relative spike signals. We then use the optical spike signals to make inferences about aggregate dynamics and produce the following estimates. Aggregates are produced in large numbers during the height of the spring bloom and sink at a rate of $\sim 75$ m d$^{-1}$. They produce a peak 2-day average 200 m carbon flux of $\sim 540$-740 mg C m$^{-2}$ d$^{-1}$, which decreased by $\sim 50\%$ by 900 m. These results broadly agree broadly with previous results from the literature and independent carbon export estimates from the North Atlantic Bloom 08 project.
ACKNOWLEDGEMENTS

I would like to thank first and foremost my advisor Mary Jane Perry for her endless support throughout all phases of my research and writing, and for bringing spikes to all of our attention in the first place. I would also like to thank my fellow lab members Emily Kallin, Ivona Cetinić, Andrea Drzewianowski, and Witek Bagniewski for their ideas, support, and collaboration. Further vital collaboration was provided by Amanda Gray, Eric Rehm, Eric D’Asaro, Craig Lee, Mike Sieracki, Nicole Poulton, Patrick Martin, Richard Lampitt, Mike Sauer, Tatiana Rynearson, Alba Gonzalez-Posada, Katherine Richardson, Nicole Bale, George Jackson, Toby Westbury, Giorgio Dall’Olmo, Dave Checkley, Ryan Rykaczewski, Katja Fennel, and Kristinn Gudmundsson. I am also grateful to my professors Huijie Xue and Emmanuel Boss for their guidance and time and my friends and fellow students Ashley Young, Alina Găinușă-Bogdan, Carrie Armbrecht, Artur Palacz, Wayne Slade, and Meg Estapa for their support, advice, and dependable help when I needed it. Thank you also to the crew and technicians on the RV-Knorr and Bjarni Saemundsson for making the collection of this data possible. I also wish to thank the National Science Foundation (Grants OCE-0628107 and OCE-0628379) and NASA (Grant NNX-08AL92G) for funding this research. Finally, I want to extend a big thank you to my wife Maki and family for their bottomless support and understanding, especially when I was lost in front of the computer screen for weeks at a time.
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Chapter 1

INTRODUCTION

Particles throughout the world’s oceans can stick together to form aggregates. These play an important role in marine biogeochemical cycles [1] particularly due to their enhanced sinking rates [2]. Rapidly sinking phytoplankton aggregates provide a major contribution to the export of organic matter from the euphotic zone, enhancing atmospheric CO₂ drawdown and delivery of organic matter to benthic ecosystems [3]. Diatom blooms in particular are known to produce rapidly sinking aggregates [4], sometimes exceeding speeds of 200 m d⁻¹ [5]. The widespread, intense phytoplankton bloom occurring each spring in the North Atlantic has been linked to large pulses of particulate material including fresh phytoplankton aggregates sinking to the ocean floor [6, 7].

The formation of these aggregates is highly dependent on the concentration and stickiness of the surface phytoplankton community [8, 9] and can vary greatly in space and time [10]. The flux of aggregates to the deep ocean is in turn dependent on their sinking speed and interactions with the heterotrophic community [3]. This variability, combined with the episodic nature of aggregation events, makes it challenging to adequately measure the spatial and temporal distribution of aggregates and thus assess their overall impact on the global carbon cycle. The ability to detect aggregates continuously, at broad spatial scales for months to years at a time, therefore, has the potential to drive significant improvements in both our estimates of carbon flux in the ocean and the models used to extend these estimates in time and space.
One method for obtaining such coverage involves small, low-power optical instruments that measure optical scattering and fluorescence and can be deployed on autonomous platforms for several months to years. Previous studies have observed occasional large spikes in the optical profiles of such instruments and interpreted them as proxies for the abundance of either aggregates or zooplankton [11-13]. In this paper, we present optical spike data from a three-month long deployment of four autonomous gliders and four accompanying cruises during the North Atlantic Bloom south of Iceland. We find a good fit between spikes in the signals of 10 optical instruments on these platforms and conclude that these spikes reliably indicate the distribution, relative abundance and chlorophyll content of aggregates within our study area with vertical and temporal resolutions of 50 m and 2 d.
Chapter 2

MATERIALS AND METHODS

2.1 Study area

Four Seagliders and a Lagrangian mixed-layer float collected data southeast of Iceland between 58.5-62.5°N and 18-28°W from 3 April to 29 June 2008 as part of North Atlantic Bloom 2008 (NAB08) experiment (Fig. 2.1). All platforms were deployed near the 60°N JGOFS site. Seagliders followed the float until 25 May when it and one glider stopped functioning correctly and were recovered. The three remaining gliders switched to bowtie surveys centered at 61.85°N, 26.2°W until the end of the experiment. Four cruises during this period supported glider deployment/recovery, sensor calibration and collection of water samples for additional biological and chemical measurements.

2.2 Platforms

2.2.1 Autonomous platforms

Seagliders are long-range, autonomous, underwater gliders that can sample up to 1,000 m depth in a sawtooth pattern and communicate while at the surface via Iridium modem [14]. Sensors onboard the gliders included temperature and salinity (Sea-Bird Electronics), pressure (Paine Corporation), optics (WET Labs ECO pucks described below), and GPS. Mean vertical speeds during the experiment ranged from 9 to 12 cm s⁻¹ and estimated horizontal speeds were 30 cm s⁻¹. Seagliders were actively piloted to follow an optically instrumented Lagrangian float that drifted within the mixed layer, surfaced daily to transmit position and data, and profiled daily to approximately 235 m
Figure 2.1. Study area for the North Atlantic Bloom 2008 project. Glider and float tracks between 3 April and 29 June 2008 are shown.
Although two gliders were swept over 100 km away from the float by strong currents before the height of the bloom, all gliders remained within 50 km of the float after 6 May (Fig. 2.2).

2.2.2 Ships

CTD and bio-optical profiles up to 600 m depth were performed during a three-week process cruise on the *R/V Knorr* from 2-21 May and three shorter cruises on the *R/V Bjarni Saemundsson* between 3-5 April, 4-5 June, and 26-29 June. A Sea-Bird Electronics 9-11 CTD, WET Labs ECO FLNTU (chlorophyll *a* fluorescence and optical backscatter) and WET Labs C-Star transmissometer profiled at 0.5 m s\(^{-1}\) between the surface and 200 m and at 1 m s\(^{-1}\) below 200 m. All CTD profiles were performed within 100 km of the float (Fig. 2.2) and all gliders, with a median CTD–glider distance <25 km.

![Figure 2.2 Distance in kilometers of gliders (gray lines) and ship profiles (black crosses) from float.](image_url)
2.3 Optical Sensors

All Seagliders had a WET Labs BB2F ECO puck that measured chlorophyll $a$ fluorescence and optical scattering (470 and 700 nm, angle of 117°). The volume sampled was approximately 1 ml over the period of 1 s. The minimum interval between samples was 5.6 s, although this interval was increased at depth to 45 s or occasionally 90 s to prolong glider battery life. BB2F sensors sampled to 600 m until 11 May and to 900 m thereafter. Three gliders also carried a WET Labs Triplet ECO puck that measured chlorophyll $a$ fluorescence, optical backscatter (532 nm, angle of 117°), and CDOM fluorescence (not reported herein). Triplet sampling strategy was similar to the BB2F until 11 May when Triplets were turned off to save energy.

A single WET Labs ECO FLNTU was used on all cruises to measure chlorophyll $a$ fluorescence and optical scattering (700 nm, angle of 140°) at a sampling rate of 1 Hz. In addition, a Seapoint Turbidity Meter for side scatter (880 nm) was used on the R/V Knorr cruise until 11 May. Two different WET Labs C-Stars with 25-cm pathlength sampling rate were used to measure the beam attenuation at 660 nm. The first C-Star was used on the April deployment cruise and in May until it malfunctioned on 11 May and was replaced by a second C-Star that was used for the remainder of the experiment. Both the Turbidity Meter and the C-Stars reported analog output at 24 Hz with time constants near 6 Hz, which was then sub-sampled at 1 Hz to agree with FLNTU output.

2.4 Data processing and inter-calibration of optical sensors

All optical sensors were factory calibrated together before and after the field experiment, with the exception of the first C-Star. Additional dark values for the ship's FLNTU were measured in situ by covering the sensor with black tape for two 600-m
profiles; these values agreed well with the manufacturer's dark values. Factory dark values were subtracted from glider optical sensor output, and additional offsets were added or subtracted to individual glider sensor output to align the pre-bloom deep-water values. Raw backscatter voltage (FLNTU) or digital counts (ECO Pucks) were then converted to volume scattering function, $\beta$, using scale factors from manufacturer's calibrations. Total particle backscatter ($b_{bp}$) was calculated following [16] using seawater backscatter coefficients of [17]. Chlorophyll $a$ fluorescence was expressed as voltage or counts minus the lowest deep-water value. C-Star voltage was converted to particulate attenuation ($c_p$) using an average of factory calibrations performed before and after the experiment for the second instrument. Values from the two instruments were aligned with an additional WET Labs C-Star on the Lagrangian float through vicarious inter-calibrations described in Section 2.4.1.

2.4.1 Glider-CTD inter-calibration

A series of intentional cross-calibration casts with nearly simultaneous ship CTD and glider profiles were carried out during the cruises, with at least two calibration profiles per glider over the entire field program. The first set of calibration profiles was made during the deployment cruise, the second during the process cruise, and the third during the recovery cruise at the end of the experiment (for two gliders only) for a total of ten cross-calibration exercises. The typical procedure was to put a Seaglider into a shallow dive sequence (to $\sim$150 m) and then hold it at the surface while the ship was brought alongside ($<50$ m). When the glider was instructed to dive, a profile was with
the ship's CTD was begun. One additional data set was collected by chance during the process cruise when a ship's CTD profile was taken within 2 km of a diving glider, yielding a total of 11 independent intercalibrations between Seaglider and ship optical sensors.

For each instrument type, optical data from the ship's CTD downcast was compared with the glider up or down optical data profile. Outliers were removed using a 5-point running median filter; profiles were further smoothed using a 7-point mean filter. CTD profiles were interpolated in density space to match each Seaglider sample. If the $r^2$ value for the linear regression between smoothed Seaglider and interpolated ship's optical
data was < 0.7, the matchup was rejected as a poor fit. Nine out of the 11 CTD profiles were retained and combined into a single type II linear regression that was used to force glider BB2F $b_{bp}$ and fluorescence to fit the ship FLNTU values (example for $b_{bp}$ in Fig. 2.3). Similar calibration profiles and analyses were performed for the float and ship optical measurements: two sets in April and 10 in May, during which the float's C-Star was used to align output of the ship's two C-Stars.

2.5 Spike Analysis

2.5.1 Separation of spikes from baseline

Spikes were observed in all optical measurements as rapid, transient and often large increases in scattering, attenuation and/or fluorescence (Fig. 3.1). Spikes were isolated by subtracting a moving “baseline” signal (7-point running minimum filter followed by 7-point running maximum filter) from the total profile (Fig. 3.2). The resulting spike signal contained both occasional large spikes and more uniform, low-level instrument noise (as seen below 150 m in Fig. 3.1a). A maximum noise threshold for each instrument was chosen as twice the 90\(^{th}\) percentile value of all of the filtered spike values taken prior to 5 May (YD 126) and below 300 m, when large spikes were rare. All spike values below this threshold were considered indistinguishable from instrument noise and set to zero. Below 200 m, where a clear baseline could always be established, we interpret the spike signal as the optical signal due to aggregates or other large particles and the baseline as the signal due to smaller particles. Above 200 m, especially in the mixed layer, there was not always a clear aggregate-free baseline, so the spike signal may be an underestimate of the entire signal due to aggregates; hence, spike signals above 200 m were not included in
further analysis. A simple Poisson model of large spike-causing particles on top of a small-particle baseline demonstrates this overestimate of the baseline filter at high concentrations of large particles (Appendix, Fig. A.1).

2.5.2 Bin averaging of spike signals

Spike signals were averaged together into 2-day, 50-m bins to compare spike signals between the four gliders (combined) and ships moving through sub-mesoscale patches with different optical properties. The bin averages included zero values (where no spike was present) and therefore depend on both spike height and spike frequency. For bins with small sample size, the correlation between platforms was low; therefore, bins with fewer than 200 data points were eliminated from further analysis. The remaining binned signals were used to compare the spike signals from different instruments (Table 2 and Figs. 3.6c,d). Baseline optical signals were bin averaged in the same fashion for comparisons between platforms (Figs. 3.6a,b). For visualization of mesoscale trends in spike and baseline data a 2-D running average with the same window size (2 d, 50 m) but moved by 0.5 d and 10 m increments was used in place of the static bins to smooth the combined data from all four gliders (Fig. 3.4).

2.6 Depth attenuation of spike signal and sinking rate estimates

Using the combined data of all four gliders, a running 2-day window was moved by 0.5-d increments from 2 to 23 May (YD 123-144) to find the maximum spike signal for each 50-m depth bin from 150 m to 850 m. In order to characterize the attenuation of spike signal with depth these maximum values were fit to a power law (Eq. 1),

\[ \text{spike signal}_z = \text{spike signal}_{100 \text{ m}} \times (z/100 \text{ m})^b \]  

(1)
analogous to the equation used by Martin et al. (1987) to describe flux attenuation, where
the exponent $b$ represents the strength of attenuation with depth. In order to estimate
aggregate sinking rate, a type I linear regression was performed between the
corresponding depths (independent variable) and times (dependent variable) of these
maximum spike signals. Ship optical data, not collected below 600 m due to instrument
pressure rating, were also used to estimate sinking rates, but could not be adequately fit to
the power law in Eq. 1.
Chapter 3

RESULTS

3.1 Patterns in optical spikes

Deep spike levels were low from the beginning of the experiment through 5 May (YD 126) (e.g. Fig. 3.1a). After 5 May (YD 126) spikes began to appear in some of the ship's optical profiles, but they were always substantially more prevalent on the downcast (e.g. Fig. 3.1b) than the upcast (e.g. Fig. 3.1c). Figure 6 shows that this decrease in spike signal on the upcast (x-axis) is strongly correlated with an increase in baseline signal (y-axis) for all optical measurements. No such difference was observed between glider dives and climbs.

Figure 3.1. Example ship optical profiles. Spikes were rare on 4 May on the downcast (a), while spikes are abundant on 10 May on the downcast (b) but reduced on upcast (c).
Figure 3.2. Isolation of spikes from an optical profile. Data come from the ship’s FLNTU $b_{bp}$ (700 nm) on 9 May (YD 130). The unfiltered 1 Hz $b_{bp}$ signal (gray line, panel A) contains large, high-frequency fluctuations ("spikes") above 400 m and smaller fluctuations (instrument noise) below 400 m. The "baseline" signal established by a 7-point running filter followed by a 7-point running maximum filter (black line, panel A) fluctuates more strongly above 200 m and is smoother below. When the baseline signal is subtracted, the remaining spike signal (gray line, panel B) that is below the minimum spike threshold (black line, panel B) is considered indistinguishable from instrument noise.
Figure 3.3. Correlations between spike loss and baseline gain on ship upcasts. A decrease in spike signals on the upcast of the ship's sampling package relative to the downcast (x-axes) is strongly correlated with an increase in baseline signals (y-axes) on each optical measurement: \( c_p \), from the C-Stars (A), raw side scatter output from the Seapoint turbidity meter (B), \( b_{bp} \) from the FLNTU (C), and raw chlorophyll fluorescence from the FLNTU (D). While the slopes of these relationships varied significantly from 0.83 (C) to 1.45 (A), coefficients of determination \( (r^2) \) were all \( \geq 0.7 \) (type II linear regression).
Figure 3.4. Contour plots of combined glider BB2F backscattering baseline (a), and spike (b) signals and chlorophyll baseline (c), and spike (d) signals. All data have been smoothed once with 2-d 50-m running means, calculated at increments of 0.5 d and 10 m, but spike signals have been smoothed a second time with a running 3.5-d 70-m window to highlight the major trends. Black lines show the best linear fits of the maximum spike signals, used to calculate sinking rates.
Table 3.1. Aggregate sinking rate estimates (95% confidence intervals). All sinking rates agree within their confidence intervals with the glider $b_{bp}$ estimate of 76 m d$^{-1}$.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Measurement</th>
<th>Sinking Rate (m d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gliders</td>
<td>$b_{bp}$ (700 nm)</td>
<td>76 (64-91)</td>
</tr>
<tr>
<td>Gliders</td>
<td>chl fluorescence</td>
<td>72 (50-131)</td>
</tr>
<tr>
<td>Ship</td>
<td>$b_{bp}$ (700 nm)</td>
<td>77 (53-143)</td>
</tr>
<tr>
<td>Ship</td>
<td>$c_p$ (660 nm)</td>
<td>76 (56-118)</td>
</tr>
</tbody>
</table>

The running means of both fluorescence and $b_{bp}$ spikes from the glider BB2Fs at 200 m began to increase substantially around 5 May (YD 126) (Figs. 3.4b,d), ~15 days after the onset of sustained phytoplankton growth at the surface (Figs. 3.4a,c). Mean spike signals peaked 4 days later at 200 m, coinciding with a peak in surface $b_{bp}$ (Fig. 3.4a) and fluorescence (Fig. 3.4c) associated with a bloom dominated by chain-forming diatoms (M. Sieracki, pers. comm.). The peak in spike signals increased in depth from 200 to 900 m at ~75 m d$^{-1}$ (Table 2). The linear fits used to calculate these sinking rates are shown by the black lines in Figs. 3.1c,d. Floating PELAGRA sediment traps deployed near the Lagrangian float and coinciding with high spike levels (May 14-15 at 600 and 750 m) caught large quantities of phytodetrital material (P. Martin and R. Lampitt, pers. comm.) including chains and viable resting cysts of the diatom *Chaetoceros sp.* (T. Rynearson, pers. comm.). The fit of the sinking spike signal with the power law in Eq. 1 shows that scattering spikes ($b = 0.45$; Fig. 2.2a) attenuated more slowly than chlorophyll fluorescence spikes ($b = 1.10$; Fig. 2.2b).

By 18 May (YD 139), the surface diatom bloom ended, chlorophyll concentrations decreased (Fig. 3.4c), and the phytoplankton community became dominated by picoeukaryotes (M. Sieracki, pers. comm.), and by 21 May (YD 142) chlorophyll...
fluorescence spikes below 200 m returned to insignificant pre-bloom levels (Fig. 3.4d). Spike signals in \( b_{bp} \) also decreased between 9 and 21 May (YD 130-142) and more slowly thereafter, but did not return to pre-bloom levels by 29 June (YD 181), the end of our experiment.

3.2 Intercomparison of optical signals

3.2.1 Unbinned optical data

Both spike and residual baseline signals from both of the BB2F scattering channels were highly correlated for all four Seagliders (Table 1), which was expected since both channels measured the same volume nearly simultaneously. Baseline \( b_{bp} \) signals from the BB2F and ECO Triplet, which were offset by \(~0.1\) m and 1-4 s were highly correlated; however, the spike signals were not. Likewise, a high correlation in baseline, but not
Table 3.2. Coefficients of determination ($r^2$) for linear regressions between spike signals from similar sensors on the same platform. With spikes removed, the baseline signals were highly correlated ($r^2 > 0.8$) for all comparisons. Unbinned spike signals were uncorrelated ($r^2 \leq 0.001$), except when both sensors shared the same sample volume ($r^2 = 0.7$). Bin averaged spike signals (2-day, 50-m averages), however, were all well correlated ($r^2 > 0.7$). Regressions were performed separately for each glider, and mean $r^2$ are ± one standard deviation are reported.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>baseline</td>
</tr>
<tr>
<td>gliders</td>
<td>BB2F - bbp700</td>
<td>BB2F - bbp470</td>
<td>0.87±0.09</td>
</tr>
<tr>
<td>gliders</td>
<td>BB2F - bbp700</td>
<td>Triplet - bbp532</td>
<td>0.91±0.02</td>
</tr>
<tr>
<td>gliders</td>
<td>BB2F - fluorescence</td>
<td>Triplet - fluorescence</td>
<td>0.96±0.005</td>
</tr>
<tr>
<td>CTD</td>
<td>FLNTU - bbp700</td>
<td>Seapoint - turbidity</td>
<td>0.93</td>
</tr>
<tr>
<td>CTD</td>
<td>FLNTU - bbp700</td>
<td>C-Star - cp</td>
<td>0.88</td>
</tr>
</tbody>
</table>

spike signal was observed between other optical datasets measured from the same platform but not the same instrument: chlorophyll fluorescence measurements for each paired glider Triplet and BB2F; FLNTU bbp vs. Seapoint turbidity and C-Star cp on the ship’s CTD Rosette system (Table 1).

3.2.2 Depth- and time-binned optical data

Although raw spike signals from different sensors on the same platform were uncorrelated, spike signals averaged in 50-m, 2-d bins were strongly correlated (Table 3.1; $r^2 > 0.7$). Between-platform correlations of 2-d, 50-m binned data from the ship’s FLNTU with BB2F data combined from all 4 Seagliders also show strong correlations for baseline particulate bbp (Fig. 3.6a; $r^2 = 0.94$) and baseline chlorophyll fluorescence (Fig. 3.6b; $r^2 = 0.93$), suggesting that sub-mesoscale variability in phytoplankton and total
Figure 3.6. Fits between 2-d, 50-m binned data (grey dots) from ship FLNTU (x-axis) and glider BB2F (y-axis). Results of type II linear regressions are shown (black lines). Panels show $b_{bp}$ baseline (A), raw chlorophyll fluorescence baseline (B), $b_{bp}$ spike signal (C), and fluorescence spike signal (D). Baseline signals (A,B) include all times and depths sampled by both ships and gliders, while spike signals (C,D) include only depths below 200 m.
particle concentrations is minimized by binning. The correlation between spike signals is slightly weaker (Figs. 3.6c,d; \( r^2 = 0.83 \) for \( b_{bp} \) and \( r^2 = 0.70 \) for chlorophyll fluorescence). The slopes of the baseline regressions (Figs. 3.6a,b) are much closer to 1 than the slopes of the spike signal regressions (Figs. 3.6c,d), indicating that while the *relative* responses of different instruments to aggregates and other large particles are consistent, the *absolute* magnitudes of these responses depend on the characteristics of the specific sensor model and/or sampling regime.
4.1 Spikes as a proxy for aggregate concentration

Multiple lines of evidence suggest that the majority of spikes reported in this study are the optical signatures of aggregates originating in the surface diatom bloom. Electronic noise is rejected as an explanation because no spikes were measured in two profiles where the FLNTU on the ship was covered with black tape, although spikes were observed on adjacent profiles. Thin layers of phytoplankton are rejected because there is no correlation between spikes in instruments 0.1 m apart (Table 2) and chlorophyll fluorescence spikes occur below the euphotic zone. The loss of spikes on the upcast of the ship’s CTD Rosette system and accompanying increase in baseline signal of all optical sensors (Fig. 3.3) can be explained if spikes are caused by fragile aggregates that are broken up in the turbulent wake of the CTD Rosette. Optical sensors were mounted near the bottom of the frame, sampling less disturbed water on the downcast and more disturbed water on the upcast. This phenomenon mirrors a recent study in which the shear created by passing a suspension of aggregates through a pump caused a decrease in particle size [18]. The chlorophyll fluorescence content of some spikes, even as deep as 900 m suggests recent origin of these spikes at the surface, which is supported by the 75 m d\(^{-1}\) sinking rate estimate. Furthermore, the capture by sediment traps of large amounts of phytoplankton material coinciding with high mean spike signals confirmed the existence of an aggregate flux event.

The good fits between binned b\(_{bp}\) spike signals from different instruments (Table 2, Figs. 3.6c,d) support the hypothesis that optical b\(_{bp}\) spikes provide a reliable proxy for
relative aggregate concentration. This indicates that optical spikes can be used to accurately capture the timing and mean sinking rates of such aggregate flux events.

While these spike signals have not been calibrated against any independent measurement of aggregate carbon content or flux, preliminary estimates of the carbon content of spike-causing aggregates were obtained using a regression between total \( b_{bp} \) (including spikes and baseline) and POC concentration measured from our ship's CTD and sampling rosette package. The sinking rate estimates reported in Table 2 were used to translate POC concentration to POC flux. These estimates carry large uncertainty for several reasons:

1. The cutoff between spike signal and baseline signal does not necessarily correspond with the cutoff between sinking and non-sinking particles. This means that some particles that are not sinking aggregates may contribute to the spike signal or some sinking aggregates may not contribute to the spike signal. The higher spike signals from the ship FLNTU vs the glider BB2F (Figs. 3.6c,d) suggest that the ship FLNTU registered a higher fraction of particles as spikes.

2. The bulk POC:\( b_{bp} \) relationship is dominated by the high particle concentrations near the surface. These particles may differ in POC:\( b_{bp} \) ratio from the sinking aggregates. Furthermore, aggregates may lose carbon as a fraction of their mass as they sink, causing an over-estimate of aggregate POC at depth.

3. If aggregates have a wide range of sinking rates, average sinking rate should increase with depth as faster particles penetrate deeper on average before being consumed. Sinking rate can also increase if aggregates become compacted with
depth (need reference). However, if the effect were large in either case, it would be reflected by non-linearity and higher uncertainty in the sinking rate estimate.

4.2 Aggregate dynamics during the North Atlantic bloom

The results of our study support current theory that diatom chains can aggregate and sink quickly following a large bloom [3-5]. After June 8 (YD 160), high chlorophyll values were observed in the surface layer (higher than chlorophyll values for the peak diatom bloom), but this time accompanied by low spike levels in the deep water column (Fig. 3.4c,d). This observation highlights the dependence of aggregate flux events on community composition, as has been observed before [19, 20]. The presence of low levels of $b_{bp}$ spikes at this time without any fluorescence spikes indicates the possibility of a lower, more constant flux of detrital aggregates and/or fecal pellets following the large diatom-associated flux event.

We obtained preliminary estimates of aggregate carbon flux during the North Atlantic Bloom from both gliders and ships, multiplying $b_{bp}$ spike signals by our POC-to-$b_{bp}$ ratio of 43000 mg C m$^{-2}$ and our sinking rate of 75 m d$^{-1}$. Between 200-250 m the maximum flux was estimated at 540 mg m$^{-2}$ d$^{-1}$ (glider) and 740 mg m$^{-2}$ d$^{-1}$ (ship), while the integrated fluxes during the period of high spike abundance between 5 and 18 May were 4.4 and 5.6 g m$^{-2}$. These differing estimates need to be reconciled with each other and validated with independent flux measurements. They are particularly dependent on the assumptions that all spike-causing aggregates sink at the same rate and that all sinking particles cause spikes, as well as the assumption that the relationship between POC and $b_{bp}$ does not change with aggregation.
If sinking rate and the relationship between POC and $b_{bp}$ do not change with depth, then the attenuation of POC flux should match the attenuation of $b_{bp}$ spikes (Fig. 3.5a; $b = 0.48$, Eq. 1). This is lower than the global range of flux attenuations from $b = 0.60$ to $1.28$ that were estimated during the JGOFS studies [21], and much lower than the estimate from the North Atlantic ($b = 1.28$). One potential explanation for this discrepancy is that aggregate carbon is consumed faster than the total aggregate material that contributes to $b_{bp}$. In this case, the attenuation of $b_{bp}$ spikes will be an under-estimate of carbon flux attenuation. The attenuation of chlorophyll fluorescence spikes, a proxy for aggregate chlorophyll concentration is closer to literature values of carbon flux attenuation (Fig. 3.5.b; $b = 1.03$, Eq. 1). This suggests that the attenuation of organic carbon during this flux event may be closer to the attenuation of aggregate chlorophyll than aggregate backscatter.

The relationship between optical spikes, aggregate carbon, and aggregate sinking rate examined by further studies measuring the response of optical instruments to known particles of different types in the laboratory and in situ.

4.3 Conclusions

We have found that autonomous gliders can reliably capture an ephemeral aggregation event within a mesoscale patch, tracking the sinking aggregates with good vertical and temporal resolution. Movement of gliders around the float and 2-day averaging smoothed out sub-mesoscale patchiness allowed characterization of the average, mesoscale-wide aggregate dynamics. The temporal and vertical resolution provided good estimates of mean aggregate sinking rate and allowed us to calculate a Martin curve that followed the sinking aggregates with time. Our specific results confirm
the existence of a brief, rapid aggregate flux event during the North Atlantic Spring bloom and estimate aggregate sinking rate at ~75 m\(^{-1}\). Attenuation of this flux with depth appears low (b \approx 0.45), but may be higher if the POC:b_{bp} ratio decreases with depth. Aggregates were fragile enough to break in the wake of a CTD rosette, and at least some aggregates contained fresh phytoplankton content. We also offer a preliminary carbon flux estimate of 4.4 to 5.6 g m\(^{-2}\) at 200 m for the duration of the 13-day flux event.

A great asset of the approach presented here is that optical instruments on autonomous platforms are already deployed worldwide and, assuming appropriate sampling frequency, post-processing of already acquired optical dataset can provide one with knowledge about the spatial and temporal distribution of aggregates.
REFERENCES


Figure A.1. Model optical profiles. Optical profiles (gray lines) are modeled as a smooth baseline (red dashed lines) with added instrument noise ($\sigma = 0.5$), and aggregates are modeled as random events following a Poisson distribution. The optical signal of each aggregate is chosen from a lognormal distribution ($\mu = 2; \sigma = 0.5$). As the average number of particles per sample ($\lambda$) increases from 0 (a) to 2 (d), "spikes" appear with greater frequency. At $\lambda = 0$ and $\lambda = 0.2$, the 7-point running baseline filter (black lines) correctly identifies the true baseline (red dashed lines). At $\lambda = 1$ (c), the baseline filter occasionally deviates from the true baseline, and at $\lambda = 2$ (d) the filter is no longer smooth and deviates significantly from the true baseline.
BIOGRAPHY OF THE AUTHOR

Nathan Briggs was born in Rhinebeck, NY on October 8, 1980. He lived in Rhinebeck for most of his childhood, with the exceptions of one year in Colchester, England during elementary school and one year in Banyoles, in the Catalan region of Spain during high school. Nathan graduated in 1999 from both his New York and Spanish high schools and went on to pursue a Bachelor’s degree in Biology at Williams College in Massachusetts, concentrating on terrestrial ecology. After graduating in 2003, Nathan worked for a year conducting field research on different bird species in New York, New Mexico, and Argentina, where he met his wife Maki. Next, he worked for two years teaching English in Kyoto Japan, then moved to Maine where he found a job as an oceanographic research technician at the Darling Marine Center and then six months later in 2008 entered the Oceanography graduate program at the University of Maine.

Nathan is a candidate for the Master of Science degree in Oceanography from the University of Maine in August, 2010.