Influence of bubbles and sand on chlorophyll-\(a\) fluorescence measurements in the surfzone

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Abstract

Continuous chlorophyll-\(a\) (Chl\(a\)) measurements in the surfzone (region of wave-breaking adjacent to the shoreline) would increase understanding of harmful algal blooms, food supply for intertidal invertebrates and fishes, and the fate of terrestrial runoff pollution. Optical measurements of Chl\(a\) fluorescence in the surfzone are affected by bubbles and suspended sand. Here, errors in surfzone Chl\(a\) fluorescence measurements (using WET Labs ECO Triplet fluorometers) are estimated by comparing observed (Chl\(a\)_raw) with known (Chl\(a\)_true) Chl\(a\) concentrations in laboratory tests with controlled amounts of bubbles and suspended sand (characterized with concurrently measured optical turbidity, \(\tau\)). For both bubbles and sand, Chl\(a\)_raw and \(\tau\) are linearly correlated, and the regression line slope depends on Chl\(a\)_true. When Chl\(a\)_true is low, Chl\(a\)_raw is biased high, and when Chl\(a\)_true is high, Chl\(a\)_raw is biased low. Fluorometers were also deployed in a natural surfzone, and for the limited range of field Chl\(a\) observed, the field and laboratory \(\tau\)-Chl\(a\) relationships were largely consistent. Mechanisms responsible for these biases are proposed, and correction procedures using the observed \(\tau\)-Chl\(a\) relationship are developed and applied to surfzone Chl\(a\)_raw observations. For the moderate Chl\(a\)_true concentrations (2–4 \(\mu\)g L\(^{-1}\)) encountered, errors in hourly mean and instantaneous Chl\(a\)_true are less than 5\% and 15\%, respectively. Larger errors are expected for Chl\(a\)_true outside this range. Although further testing is needed, the results suggest that in situ, optical Chl\(a\)_raw from other turbid environments (e.g., estuaries, bays) should also be interpreted cautiously.

Introduction

Chlorophyll-\(a\) fluorescence (Chl\(a\)), often used as a proxy for phytoplankton biomass (e.g., Falkowski and Kiefer 1985), is measured by laboratory extraction from discrete water samples (Chl\(a\)_raw) or continuously with in situ optical fluorometers (Chl\(a\)_true). The fast sampling and convenience of in situ optical instruments are advantageous, and in situ Chl\(a\) sampling is common in the open ocean and on continental shelves. Light scattering near the ocean surface is generated by a variety of seawater constituents, including bubbles, sand, plankton, and detritus (e.g., Stramski et al. 2004). The relative contributions of these constituents to the total light scattering are variable over time and space. For example, beneath open-ocean breaking waves, bubble-induced light scattering spans several orders of magnitude over time periods of minutes (Terrill et al. 2001). Optical Chl\(a\) measurements are affected by scattering from particulates, and so data from very near the surface and seafloor (where the concentration of scatterers is highest) are often discarded.

Continuous Chl\(a\) measurements in the surfzone (region of wave-breaking adjacent to the shoreline) could aid understanding of harmful algal blooms, food supply for intertidal invertebrates and fishes, and the fate of terrestrial runoff pollution. Because of wave breaking and strong currents in shallow water (few meters depth), sediment suspended from the sea bottom, and bubbles injected at the surface, can intermittently populate the entire water column (e.g., Deane and Stokes 1999). The relative contributions of sand and bubbles to a point measurement of surfzone light scatter is not understood, but backscatter is known to depend on cross-shore location and distance above the seafloor (Wang et al. 2002). Backscattered light is known to be problematic for accurate measurement of fluorescent dye with benchtop fluorometers.

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(Smart and Laidlaw 1977) and in situ in the surfzone (Clark et al. 2009). In this article, we characterized the fluorometer response in turbid water and developed methods to correct continuously observed Chl$_a$ in the surfzone and (potentially) other turbid environments.

Turbidity from a calibrated nephelometer ($\tau$, nephelometric turbidity units or ntu) characterizes the water cloudiness by observing the amount of emitted light that is backscattered by particles, relative to a secondary standard of clear water. Turbidity depends on the particle concentration, size, shape, and internal index of refraction, as well as the emitted light wavelength and details of the optics (e.g., Zaneveld et al. 1979). The single-frequency turbidity sensors used here provide a bulk estimate of the scattering by all particles in the sample volume.

The influence of bubbles and sand on Chl$_{aq}$ is explored by simultaneously measuring Chl$_{aq}$ and $\tau$ with a WET Labs ECO Triplet fluorometer. Two $\tau$-related mechanisms can distort ECO Triplet Chl$_{aq}$ (Fig. 1A). Sand and bubbles can scatter light emitted from the $\tau$ channel into the Chl$_a$ detector. The wavelength ranges of the $\tau$ emitter and Chl$_a$ detector overlap (personal communication, WET Labs personnel, technical specifications unavailable), elevating (e.g., enhancing) Chl$_{aq}$ (mechanism A, Fig. 1A). This mechanism is explored by observing Chl$_{aq}$ with and without the $\tau$ emitter blocked. Sand and bubbles also scatter and absorb excited and fluoresced light away from the Chl$_a$ emitter/detector, thereby reducing Chl$_{aq}$ (mechanism B, Fig. 1B). This mechanism is evaluated over a range of bubble- and sand-induced $\tau$ for a range of known Chl$_{aq}$ concentrations. Fluorometers were also deployed in a natural surfzone, and field and laboratory $\tau$-Chl$_a$ relationships were consistent within the limited range of field Chl$_a$ observed. Correction procedures using the observed $\tau$-Chl$_a$ relationship were developed and applied to surfzone Chl$_{aq}$ observations. The effect of fluorescent dye (mechanism C, Fig. 1C) and sunlight (mechanism D, Fig. 1D) on Chl$_{aq}$ and the $\tau$ response of a flow-through WET Labs WETStar fluorometer are discussed in the appendix.

**Materials and procedures**

**ECO Triplet fluorometer**—Laboratory and field tests used four 3-channel WET Labs ECO Triplet Fluorometers (www.wet-labs.com) that measure Chl$_a$ (470/695 nm excitation/emission wavelengths, 0–150 µg L$^{-1}$ range), Rhodamine-WT dye (540/570 nm excitation/emission wavelengths, 0.2–500 ppb range), and backscattered turbidity (660 nm wavelength, 0.03–100 ntu range). In the field, ECO Tripllets internally stored the 3.8-s average of 8-Hz samples. In the lab, 8-Hz samples were averaged for about 1 s. Before testing, the ECO Tripllets were calibrated with natural phytoplankton populations (collected from the SIO pier) to within 4% of the WET Labs–provided Chl$_a$ calibration. The WET Labs–provided calibration for turbidity was used to convert the backscatter from counts to units of ntu.

**Laboratory methods**—To reduce the effect of ambient light, laboratory tests were performed in a round 15-L (30 cm diameter) black-lined bucket with a downward pointing ECO Triplet. In fresh, Chl$_a$-free water, boundary effects (significant and slight enhancement in $\tau$ and Chl$_{aq}$, respectively) were evident only within 5 cm of the bucket wall or bottom. Elsewhere $\tau$ and Chl$_{aq}$ were near zero, indicating minimal interference from bucket wall reflections where the tests below were performed.

The effect of bubble-generated $\tau$ on Chl$_{aq}$ was measured by injecting, into water with known Chl$_{aq}$, controlled quantities of bubbles using a balsa wood bubbler attached to the end of an air hose. The hose air pressure was adjusted so that the bubble-induced $\tau$ range was similar to surfzone field tests (0–90 ntu). Nominal bubble radius ranged from 1 to 5 mm, representative of surfzone bubbles (Deane and Stokes 1999).

Similar tests were done with controlled amounts of suspended sand. Dry sand from Scripps Beach (mean diameter approximately 0.2 mm) was kept in a dry, dark container for at least 1 week to eliminate fluorescence from live phytoplankton attached to the grains. Sand-induced $\tau$ was generated by stirring up to 200 g of dry sand in the 15-L bucket. Laboratory
sand concentrations (0–13 g L^{-1}) were comparable to instantaneous near-bed concentrations observed in sandy beach surfzones (e.g., Yu et al. 1993, Beach and Sternberg 1996), and the turbidity range was similar to field observations (0–90 ntu).

Phytoplankton, obtained by towing 60-µm mesh nets from the SIO pier in La Jolla, CA, were mixed with sand-filtered (Chlα -0.1 µg L^{-1}) seawater to obtain five samples (10 L each) with Chlα between 0.2 and 10 µg L^{-1}. Chlα_{true} was measured by filtration of a 150-mL water sample onto 25-mm GF/F filters, extraction in 10 mL acetone, and assessment with a calibrated Turner Designs 7000 benchtop fluorometer. Three extractions at each Chlα concentration indicate reproducibility to less than 0.5 µg L^{-1}.

Chlα_{raw} field measurements—A month-long field experiment was conducted at Huntington Beach, CA, in fall 2006. Seven bottom-mounted instrumented (temperature, pressure, and current) frames were deployed on a 160-m long cross-shore transect (from 0 to 4 m depth, relative to mean sea level), that spanned the surfzone for the wave conditions encountered. Pressure sensor data were used to calculate hourly significant wave height and the tidally varying mean sea surface. Four ECO Triplet fluorometers were repeatedly deployed for 72-h periods on different frames, facing 30 degrees from down-slope, nominally 50 cm above the seafloor.

Assessment

In undisturbed (no bubbles or sand) freshwater with Chlα_{true} = 0, τ and Chlα_{raw} were approximately 0 ntu and 0 µg L^{-1}, respectively (Fig. 2, shaded region from 0–50 s). With the addition of bubbles, τ and Chlα_{raw} spiked as high as 95 ntu and 7 µg L^{-1}, respectively (Fig. 2, nonshaded regions). When bubbling stopped, τ and Chlα_{raw} dropped to near zero (Fig. 2, gray-shaded region near 205 s). Sporadic Chlα_{raw} spikes occurred (e.g., Chlα_{raw} = 7 µg L^{-1} at time 190 s, Fig. 2) and were filtered by rejecting data where the Chlα_{raw} rate of change exceeded 1 µg L^{-1} s^{-1}, a threshold selected to remove large spikes while retaining most of the data. This spike filter, applied to all laboratory Chlα_{raw} data, removed between 15% and 35% of data points. After spike removal, Chlα_{raw} and bubble-induced τ were significantly correlated (slope \([\alpha] = 0.008 \pm 0.001 \text{ µg L}^{-1} \text{ ntu}^{-1}, r^2 = 0.41, P < 0.001\) (Fig. 3A), indicating that mechanism A (Fig. 1A) enhances the measured Chlα_{raw}. Similarly, Chlα_{raw} and sand-induced τ were correlated (\([\alpha] = 0.0046 \pm 0.0005 \text{ µg L}^{-1} \text{ ntu}^{-1}, r^2 = 0.64, P < 0.001\) (Fig. 3C). The τ-induced enhancement was reproduced in all four ECO Triplets tested.

To confirm that light from the τ channel enhances Chlα (mechanism A, Fig. 1A), the Chlα = 0 τ tests were repeated with the τ light excitation blocked on one ECO Triplet. A second, adjacent ECO Triplet measured τ. After spike-filtering, τ excitation-blocked Chlα_{raw} was near zero and uncorrelated with τ for both sand and bubbles (Fig. 3B,D), confirming that for these Chlα_{true} = 0 tests, the dominant noise source is enhancement from the τ channel.

In seawater with Chlα_{true} = 10 µg L^{-1} (typical of a coastal phytoplankton bloom), the τ-Chlα_{raw} relationship is opposite that for Chlα_{true} = 0 µg L^{-1} (Fig. 4). In undisturbed seawater, τ remained steady at 5 ntu (shaded regions in Fig. 4). When bubbles were added, Chlα_{raw} and τ were inversely related (unshaded regions in Fig. 4), with Chlα_{raw} decreasing by 40% at high τ, indicating that mechanism B (Fig. 1B) is dominant. When bubble injection intermittently ceased (gray-shaded regions, Fig. 4), τ and Chlα_{raw} returned to undisturbed levels.

The observed τ and Chlα_{raw} (at fixed Chlα_{true}) are linearly related (Fig. 5) and may be described by the following equation:

\[
\text{Chlα}_{raw}(\tau) = \text{Chlα}_{true} + \gamma \tau.
\]  

Nonlinear (quadratic and exponential) fits were also explored, but did not improve the goodness of fit (e.g., Akaike and Bayesian Information Criteria [AIC-BIC], Schwarz 1978). For bubble-induced turbidity tests (Fig. 5A), the slope (\(\gamma\)) of the τ-Chlα_{raw} fit depends on Chlα_{true}, ranging from enhancement at 0.2 µg L^{-1} (mechanism A) to strong suppression at 10 µg L^{-1} (mechanism B). Near Chlα_{true} = 4 µg L^{-1}, γ ~ 0 and the two mechanisms approximately cancel. Sand-generated τ and Chlα_{raw} show a similar, but less pronounced, pattern (Fig. 5B).

A proposed model for the relationship between Chlα_{raw} and τ is

\[
\text{Chlα}_{raw}(\tau) = \text{Chlα}_{true} + \alpha_+ + \beta_+ (\text{Chlα}_{raw}) \tau,
\]
where the second and third terms on the righthand side represent mechanisms A and B, respectively, $\alpha$ and $\beta$ are empirically determined constants, and the exponent $n$ is an integer. Using Eq. 2, the dependence of the slope $\gamma$ (Eq. 1) on Chl$_{\text{true}}$ is

$$\gamma = \alpha + \beta_n(\text{Chl}_{\text{true}})^n.$$  (3)

In agreement with Eq. 3, $\gamma$ observed depends nearly monotonically on Chl$_{\text{true}}$ and model fits with $n = 1$ and $n = 2$ were explored (solid and dashed curves in Fig. 6). For the bubbles tests, the quadratic fit ($n = 2$) improved the AIC-BIC over the linear fit ($n = 1$); however, both are encompassed with the error bars on $\gamma$ at Chl$_{\text{true}} < 10 \mu g$ L$^{-1}$. For the sand tests, the linear fit was most appropriate (black line in Fig. 6). Choice of an optimal model (linear or quadratic) likely will depend on the observed Chl$_{\text{true}}$ range. For small ranges in Chl$_{\text{true}}$, the quadratic approaches the linear model, whereas for a large range in Chl$_{\text{true}}$, the relationship will be strongly dependant on the choice of $n$. Bubble-generated turbidity yields $\beta_2 \sim 0.001 \mu g$ L$^{-1}$ ntu$^{-1}$ for the quadratic fit, and $\beta_1 \sim 0.01$ ntu$^{-1}$ (nearly 10 times larger than the $\beta_1 \sim 0.001$ ntu$^{-1}$ for sand). For single-channel fluorometers (no $\tau$ channel), suppression (mechanism B) is present. Tests with a single channel WETStar fluorometer and a separate $\tau$ sensor in a flow-through package agree qualitatively with Eq. 2 with $\alpha = 0$ (Appendix 1C).

The laboratory tests were conducted with either bubbles or sand only. In the surfzone, bubbles and sand are both present, in unknown amounts, so the appropriate $\alpha$ and $\beta_n$ for field applications are unknown. The $\alpha$ and $\beta_n$ obtained from sand-only and bubble-only lab tests are considered an envelope for the range in Chl$\alpha$ error.
Surfzone field observations are examined in light of laboratory tests showing that turbidity generates Chl$_{a}$ errors that depend upon Chl$_{a}$$_{true}$. Field data were retained only if the ECO Triplet was more than 1 m below the mean free surface, thus reducing the effect of scattered sunlight (Appendix 1C) and excluding observations (usually at low tide) when the sensor pierced the water surface in wave troughs. The spike filter (a cutoff of 0.25 µg L–1 s–1 was chosen for field data because the ECO Triplets were sampled at 0.25 Hz rather than the 1-Hz lab sample rate) removed obvious Chl$_{a}$$_{raw}$ spikes while preserving 95% of the data.

Laboratory tests examined τ-induced errors in Chl$_{a}$$_{raw}$ with known, fixed Chl$_{a}$$_{true}$ (Figs. 4, 5, and 6). Field data segments are selected for comparable analysis. Chl$_{a}$$_{nat}$ for each 3-h segment is defined as the Chl$_{a}$$_{raw}$ values when τ < 10 ntu (gray points, Fig. 7). Of 250 original segments, 85 were retained with (1) small Chl$_{a}$$_{nat}$ variation (standard deviation < 1 µg L–1) and (2) broad variation in τ (upper τ limit > 50 ntu). For the 85 cases, Chl$_{a}$$_{raw}$ was typically low (< 5 µg L–1), and Chl$_{a}$$_{raw}$ and τ were often significantly correlated ($r^2$ ranging between 0.2 and 0.6). Linear best fits between Chl$_{a}$$_{raw}$ and τ yield γ values for each 3-h segment (Fig. 7) that are similar to laboratory γ with known, fixed Chl$_{a}$$_{true}$ (Fig. 5). Extracted Chl$a$ from bottle samples were not available for each of these time periods and fluorometer locations, thus the median Chl$_{a}$$_{nat}$ (Chl$_{a}$$_{m\-nat}$) was assumed to approximate Chl$_{a}$$_{true}$. The field γ–Chl$_{a}$$_{m\-nat}$ relationship (where τ is caused by a mix of bubbles and sand) is bounded by the results from lab tests with sand and bubbles introduced separately (shaded region, Fig. 8). The field Chl$_{a}$$_{m\-nat}$ range is limited between 1 and 4 µg L –1. Within this range, a quadratic relationship between γ and Chl$_{a}$$_{m\-nat}$ did not improve the fit (according to the AIC-BIC). Therefore, for the observed Chl$_{a}$$_{m\-nat}$ range, a linear model ($n = 1$) was considered most appropriate. For larger Chl$_{a}$$_{true}$ this may not be appropriate. The γ–Chl$_{a}$$_{m\-nat}$ relationship may differ within and seaward of the surfzone owing to the different contributions of breaking wave-induced bubbles and sand to turbidity. However, the fit skill and intercept within and seaward of the surfzone are not statistically different, so an α$_{field}$ and β$_{field}$
Typical variations of \( \tau \), tides, waves, and Chl\( \alpha \) are illustrated with 48 h of observations at two fixed locations, one within the surfzone, and the other further seaward (Fig. 9). Wave heights at the seaward location varied less than 10% from 0.55 m (Fig. 9C). At lower tide stages, the shallow instrument was near the surface, occasionally exposed in wave troughs, and \( \tau \) and Chl\( \alpha \)raw were noisy (Fig. 9A and D). Data from less than 1 m below the surface were discarded, and spikes removed (black line, Fig. 9E). Corrections for the \( \tau \)-induced errors are based on Eq. 2, with \( n = 1 \):

\[
\text{Chl}_{\text{raw}}(\tau) = \frac{\text{Chl}_{\text{true}}(\tau) + \alpha_{\text{raw}} \tau(\tau)}{1 + \beta_{\text{raw}} \tau(\tau)}
\]

where \( \tau \) is time. The corrected (red line, Fig. 9E) and raw (black line, Fig. 9E) data are similar for the range of Chl\( \alpha \)raw for this period. The black dashed line is a linear best fit (slope \( \gamma = 0.0086 \mu g \text{ L}^{-1} \) ntu\(^{-1} \), \( \beta = 0.29 \), \( P < 0.001 \)).

Within the surfzone (~20 m from shore), \( \tau \) ranged between 2 and 7 \( \mu g \text{ L}^{-1} \) (gray lines, Fig. 10). Wave heights at the seaward location varied less than 10% from 0.55 m (Fig. 9C). At lower tide stages, the shallow instrument was near the surface, occasionally exposed in wave troughs, and \( \tau \) and Chl\( \alpha \)raw were noisy (Fig. 9A and D). Data from less than 1 m below the surface were discarded, and spikes removed (black line, Fig. 9E). Corrections for the \( \tau \)-induced errors are based on Eq. 2, with \( n = 1 \):

\[
\text{Chl}_{\text{raw}}(\tau) = \frac{\text{Chl}_{\text{true}}(\tau) + \alpha_{\text{raw}} \tau(\tau)}{1 + \beta_{\text{raw}} \tau(\tau)}
\]

where \( \tau \) is time. The corrected (red line, Fig. 9E) and raw (black line, Fig. 9E) data are similar for the range of Chl\( \alpha \)raw encountered. The instantaneous (and hourly mean) errors induced by \( \tau \) reach 15% (5%) within the surfzone (black line, Fig. 9E) and are negligible seaward (gray line, Fig. 9F). With the modest range of observed Chl\( \alpha \)true, the model (Eq. 1) predicts that \( \tau \)-induced errors in Chl\( \alpha \)true seaward of the surfzone would be limited to 1% (at 5 ntu), whereas errors within the surfzone would surpass 15% (above 30 ntu).

Turbitity depended on the cross-shore location (within or seaward of the surfzone) and decreased with depth below the surface. At the most-offshore fluorometer (~160 m from shore), \( \tau \) was below 5 ntu 90% of the time, and Chl\( \alpha \)true typically ranged between 2 and 7 \( \mu g \text{ L}^{-1} \) (gray lines, Fig. 10). Within the surfzone (~20 m from shore), the \( \tau \) range was larger, falling below 30 ntu 90% of the time, and the Chl\( \alpha \)true range was smaller than offshore (black lines, Fig. 10).

Natural Chl\( \alpha \)true variability may be driven by advection of horizontal and vertical phytoplankton patches, cell growth and death, phytoplankton behavior (swimming or sinking), or physiological adaptations to light. Nearshore Chl\( \alpha \) levels are often variable. For example, Chl\( \alpha \)true was < 1 \( \mu g \text{ L}^{-1} \) 10.0% and > 10 \( \mu g \text{ L}^{-1} \) 7.4% of the time in biweekly bottle samples from the SIO pier (~5 m total depth; La Jolla, CA, SCCOOS.org) between April 2005 and April 2008. During these time periods, if \( \tau \) reached 50 ntu, bubble- and sand-induced ECO Triplet errors (assuming a linear [\( n = 1 \)] relationship between \( \gamma \) and Chl\( \alpha \)true) would be on the order of 80% (low Chl\( \alpha \)true) and 20% (high Chl\( \alpha \)true), respectively (Fig. 11a). In single-channel fluorometers when mechanism A is not present, the ratio between Chl\( \alpha \)true and Chl\( \alpha \)true would depend on \( \tau \), and under moderate surfzone conditions (30 ntu) and moderate Chl\( \alpha \)true Chl\( \alpha \)true would underestimate Chl\( \alpha \)true by 15% (Fig. 11B). In some highly productive areas, Chl\( \alpha \)true frequently surpasses 10 \( \mu g \text{ L}^{-1} \), and during intense blooms, may reach >100 \( \mu g \text{ L}^{-1} \) (e.g., Kudela and Cochlan 2000). Under these circumstances, a more detailed investigation of the nonlinear relationship between Chl\( \alpha \)true and \( \gamma \) (see Fig. 6) is required.

Sudden, intense appearances of specific species of phytoplankton are known as harmful algal blooms (HABs) because of toxins (e.g., *Pseudo-nitzschia* spp., Sayce and Horner 1996), mechanical damage (e.g., *Chetoceros* spp., Tester and Mahoney 1995) or anoxia (e.g., *Ceratium* spp., Mahoney and
Fig. 9. (A) Turbidity $\tau$. (B) Depth $d_{bs}$, distance instrument is below mean sea surface (dashed line is 1 m). (C) Significant wave height $H_{sig}$. (D) Unprocessed Chl$_{raw}$. (E) Surfzone Chl$_{raw}$ (despiked, observations within 1 m of the surface removed, black) and Chl$_{corr}$ (red). (F) Chl$_{raw}$/Chl$_{corr}$ All versus time for 48 h. Gray (black) lines correspond to data seaward of (within) the surfzone.
Steml 1979) associated with them. The greatest ecological and economic costs incurred by HABs are observed in nearshore environments where benthic populations and aquaculture are exposed. Satellite-derived Chlα estimates are commonly used for HAB monitoring. Pfister et al. (2007) compared Chlα data from SEAWIFS satellite measurements and a flow-through WETStar fluorometer moored within a tide pool (1.1 m total depth) at Tatoosh Island, WA. Despite various quality controls, remotely sensed Chlα and moored Chlα were poorly correlated. Pfister et al. (2007) suggested a variety of explanations that may have contributed to the poor correlation. An additional explanation for the poor correlation may be the turbidity-induced error in this shallow nearshore environment (see Appendix 1C for bubble-induced Chlαraw error with a WETStar fluorometer). This poor correlation emphasizes the importance of extensive comparisons between satellite and in situ monitoring stations, and also the necessity for improved understanding of the potential instrument response in these sometimes turbid environments.

Comments and recommendations

The effect of bubble- and sand-generated turbidity on measured Chlα fluorescence has been estimated for WET Labs ECO Triplet fluorometers using both laboratory tests and field observations. The results are summarized as follows: (1) Sporadic spikes in Chlαraw (in lab and field) are common under turbid conditions and can be removed. (2) For low Chlαtrue concentrations (<4 µg L–1), turbidity enhances the Chlαraw signal by scattering a fraction of the emitted τ light into the Chlα detector (mechanism A, Fig. 1A). For Chlαtrue > 4 µg L–1, turbidity reduces Chlαraw relative to Chlαtrue by scattering or absorbing emitted and fluoresced light before detection (mechanism B, Fig. 1B). Laboratory tests indicate that the presence of bubbles or sand (after despiking) induces a false Chlαraw signal of up to 1 µg L–1 in Chlα-free water, and Chlαraw suppression of up to 40% (in water with nonzero Chlα) at typical surfzone turbidity levels. (3) In general, Chlαraw is more affected by bubble-generated turbidity than by sand-generated turbidity for both mechanism A and mechanism B, but particularly at high Chlαtrue when mechanism B dominates. (4) A linear (n = 1) model for the τ-Chlαraw slope (γ) best rep-
resents the limited range of Chl\textsubscript{a\ raw} observed in the field. The dependence of $\gamma$ on Chl\textsubscript{a\ true} ($\sim$Chl\textsubscript{a\ m-nat}) is consistent between lab and field observations, suggesting that the laboratory tests were representative of field surfzone conditions. Although a quadratic ($n = 2$) model best described the laboratory tests with bubble-induced turbidity, a linear model was the most appropriate for our limited field data set. (5) This $\tau$–Chl\textsubscript{a\ raw} model can be used to approximately correct data and to estimate error bounds for Chl\textsubscript{a\ true} less than 10 µg L\textsuperscript{-1}. Observations over a greater range of Chl\textsubscript{a\ true} are required before extrapolating the linear model for $\gamma$ to correct high Chl\textsubscript{a\ raw} concentrations. (6) Rhodamine-WT dye generates a strong false Chl\textsubscript{a} signal and therefore precludes reliable coincident measurements of Chl\textsubscript{a} (mechanism C, Fig. 1C; Appendix 1A). (7) Incident irradiance may enhance Chl\textsubscript{a\ raw} less than 1 m below the surface (mechanism D, Fig. 1D; Appendix 1B). (8) Bubble-induced turbidity generated qualitatively similar suppression (mechanism B) in a single-channel, flow-through Wetstar fluorometer (Appendix 1C), indicating that this effect applies generally to other fluorometers, not just the ECO Triplet. Caution is recommended in interpreting in situ Chl\textsubscript{a\ raw} data from turbid environments.

References


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