Chlorophyll biomass in the global oceans: airborne lidar retrieval using fluorescence of both chlorophyll and chromophoric dissolved organic matter

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For three decades airborne laser-induced fluorescence has demonstrated value for chlorophyll biomass retrieval in wide-area oceanic field experiments, satellite validation, and algorithm development. A new chlorophyll biomass retrieval theory is developed using laser-induced and water Raman normalized fluorescence of both (a) chlorophyll and (b) chromophoric dissolved organic matter (CDOM). This airborne lidar retrieval theory is then independently confirmed by chlorophyll biomass obtained from concurrent (1) ship-cruise retrievals, (2) satellite inherent optical property (IOP) biomass retrievals, and (3) satellite standard band-ratio chlorophyll biomass retrievals. The new airborne lidar chlorophyll and CDOM fluorescence-based chlorophyll biomass retrieval is found to be more robust than prior lidar methods that used chlorophyll fluorescence only. Future research is recommended to further explain the underlying influence of CDOM on chlorophyll production.

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1. Introduction

Retrieval of chlorophyll biomass [denoted herein by ⟨Chl⟩ in units of milligram per cubic meter] retrieval by airborne laser-induced chlorophyll fluorescence emission at ~683 nm, $F_{chl}(683)$, was reported more than three decades ago.[1] Subsequently, airborne lidar retrieval of chlorophyll biomass was improved by normalizing the $F_{chl}(683)$ emission signal by the concurrent OH-stretch water Raman emission, R, found $\sim 3250\ cm^{-1}$ from the laser excitation.[2] The water Raman normalization formulation, $F_{chl}(683)/R$, reduces uncertainty in the chlorophyll fluorescence signal because of the: (1) laser transmitter power fluctuations, (2) aircraft height and attitude variations, (3) atmospheric transmission variability, and (4) horizontal spatial variability in the water column attenuation coefficient.

The F_{chl}/R product was used to infer chlorophyll biomass spatial variability in the ocean.[3] The data were acquired with the popular frequency doubled Nd:YAG laser at 532 nm, whose OH-stretch water Raman occurs at ~645 nm.[4] Thus the chlorophyll fluorescence–to–water Raman ratio $F_{chl}(683)/R(645)$ was used. The water Raman normalization technique was applied to both phytoplankton chlorophyll and phycoerythrin pigment fluorescence and used in still larger oceanic airborne lidar experiments to infer phytoplankton species variability in the western North Atlantic Ocean.[5,6]

To address the development and validation of satellite passive (solar) retrieval algorithms for chlorophyll and phycoerythrin biomass, the Raman normalized pigment fluorescence emissions were also used to develop empirical reflectance ratio and semianalytical algorithms to retrieve chlorophyll and phycoerythrin biomass.[7,8,9,10] To address the important task of satellite algorithm development using semianalytical in-water radiative transfer methods, a slight but very decisive departure was made in the application of $F_{chl}(683)/R(645)$, which is used as a surrogate for phytoplankton absorption coefficient, a_{ph}, with notable success in forward modeling of oceanic upwelled reflectance.[11] I.e., it was assumed that $a_{ph} = \text{constant} \times F_{chl}(683)/R(645)$. This successful a_{ph} assumption was prompted by explicit analogy to a similar successful algorithm for chromophoric dissolved organic matter (CDOM) absorption coefficient a_{CDOM},[12,13] previously developed by using the fre-

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quency tripled Nd:YAG laser to yield $a_{CDOM} \propto F_{CDOM}(450)/R(402)$. Similarly, a robust connection between a_{ph} and $F_{chl}(683)/R(645)$ was also found in subsequent airborne and satellite radiative transfer model inversion retrievals of a_{ph} from water leaving reflectances.[10,14] I.e., it was found that the a_{ph} retrieved from inversion of oceanic reflectances was highly correlated with $F_{chl}(683)/R(645)$. Thus, herein, we use $a_{ph} \propto F_{chl}(683)/R(645)$ in addition to the well-established result that $a_{CDOM} \propto F_{CDOM}(450)/R(402)$.

While recently published works[10,11,14,15] strongly suggest that $a_{ph} \propto F_{chl}(683)/R(645)$, the chlorophyll biomass versus $F_{chl}(683)/R(645)$ relationship was not yet fully reconciled. As another example, our very recent attempts to validate satellite derived chlorophyll biomass by using airborne $F_{chl}(683)/R(645)$ yielded rather mixed results that were reconciled only by inclusion of a CDOM absorption component.[16] The need for CDOM absorption in $\langle \mathrm{Chl} \rangle$ retrieval was a surprising finding. The inclusion of CDOM absorption in our $\langle \mathrm{Chl} \rangle$ retrieval is, however, in agreement with other researchers who found that (1) chlorophyll biomass retrievals using reflectance band ratios are proportional to a_{ph} and a_{CDOM}[17] in ship cruise experiments, (2) there is a correlation between a_{ph} and a_{CDOM} in ship data,[18] and (3) that there is a strong correlation between a_{ph} and a_{CDOM} when compared to global in situ chlorophyll data.[16]

Therefore it is our objective in this paper to provide a retrieval theory and experimental results that strongly suggest that airborne lidar retrieval of $\langle \mathrm{Chl} \rangle$ is best achieved by using both $F_{chl}(683)/R(645)$ and $F_{CDOM}(450)/R(402)$. Future research will explore the fundamentals of why both[16] a_{ph} and $F_{CDOM}(450)/R(402)$, or their surrogates $F_{ch}(683)/R(645)$ and $F_{CDOM}(450)/R(402)$ are required for chlorophyll biomass retrieval.

2. Theory: Chlorophyll Biomass Retrieval by Airborne Laser-Induced Chlorophyll and CDOM Fluorescence

Using laboratory and field experiments together with radiative transfer theory, it has been shown[16] that a viable IOP-based chlorophyll biomass algorithm $\langle \mathrm{Chl} \rangle$ is given by

$$\langle \mathrm{Chl} \rangle = \exp(q_5 x^5 + q_4 x^4 + q_3 x^3 + q_2 x^2 + q_1 x + q_0), \tag{1}$$

where

$$x \equiv \ln[a_{ph} + p(a_{CDOM})^{1/2}]. \tag{2}$$

As before, a_{ph} and a_{CDOM} are, respectively, the absorption coefficients of phytoplankton CDOM, and the tabulated[16] q_i's and p are constants determined by least squares. The inclusion of the square root on a_{CDOM} is purely a tool to improve the performance of the satellite IOP-based empirical algorithm[16] and, as will be seen, is not utilized within the airborne algorithm.

The satellite IOP-based algorithm in Eqs. (1) and (2) has been shown to be comparable with the standard SeaWiFS OC4v4 reflectance ratio retrievals that use more than 2,000 ship-based biomass values.[16]

Table 1. Numerical Constants for Algorithm Eqs. (5) and (6)

Constant	Value
Q_0	0.2033
Q_1	1.3010
Q_2	1.1407
Q_3	−0.0453
P	3.25

For lidar remote sensing, the a_{CDOM} absorption coefficient IOP has been shown to be linearly related to the 355-nm laser-induced and water Raman normalized CDOM fluorescence,[12–15]

$$a_{CDOM} \propto [F(450)/R(402)] \equiv \mathrm{CDOM}_{F/R}, \tag{3}$$

where $F(450)$ is the CDOM fluorescence at 450 nm and $R(402)$ is the concurrent Raman backscatter at 402 nm.

Thus a similar relationship is used as a surrogate for the phytoplankton absorption coefficient IOP,[14,15]

$$a_{ph} \propto [F(683)/R(645)] \equiv \mathrm{Chl}_{F/R}, \tag{4}$$

where $F(683)$ is the phytoplankton chlorophyll fluorescence at 683 nm, and $R(645)$ is the concurrent Raman backscatter at ~645 nm. Equation (4) is valid, since airborne laser pump and probe results have shown that phytoplankton variable fluorescence[19,20] is not easily detectable during daylight hours of satellite overflight when airborne lidar underflights are usually conducted.

Then, in analogy to the satellite result, the chlorophyll biomass retrieval algorithm for airborne laser data is formulated as

$$\langle \mathrm{Chl} \rangle = \exp(Q_3 X^3 + Q_2 X^2 + Q_1 X + Q_0), \tag{5}$$

where

$$X \equiv \ln[\mathrm{Chl}_{F/R} + P \times \mathrm{CDOM}_{F/R}]. \tag{6}$$

Least-squares determination of the constants Q_0, Q_1, Q_2, Q_3, and P within Eqs. (5) and (6) completes the airborne laser determined $\langle \mathrm{Chl} \rangle$. Table 1 gives the values for the algorithm constants Q_0, Q_1, Q_2, Q_3, and P.

3. Results

The new airborne lidar chlorophyll biomass retrieval of $\langle \mathrm{Chl} \rangle$ in Eqs. (5) and (6) is demonstrated through four field experiments as discussed below.

First, 16 ship-derived chlorophyll biomass values from a 3–10 May 1998 cruise are found to be contemporaneous with a 8 May 1998 airborne lidar over-

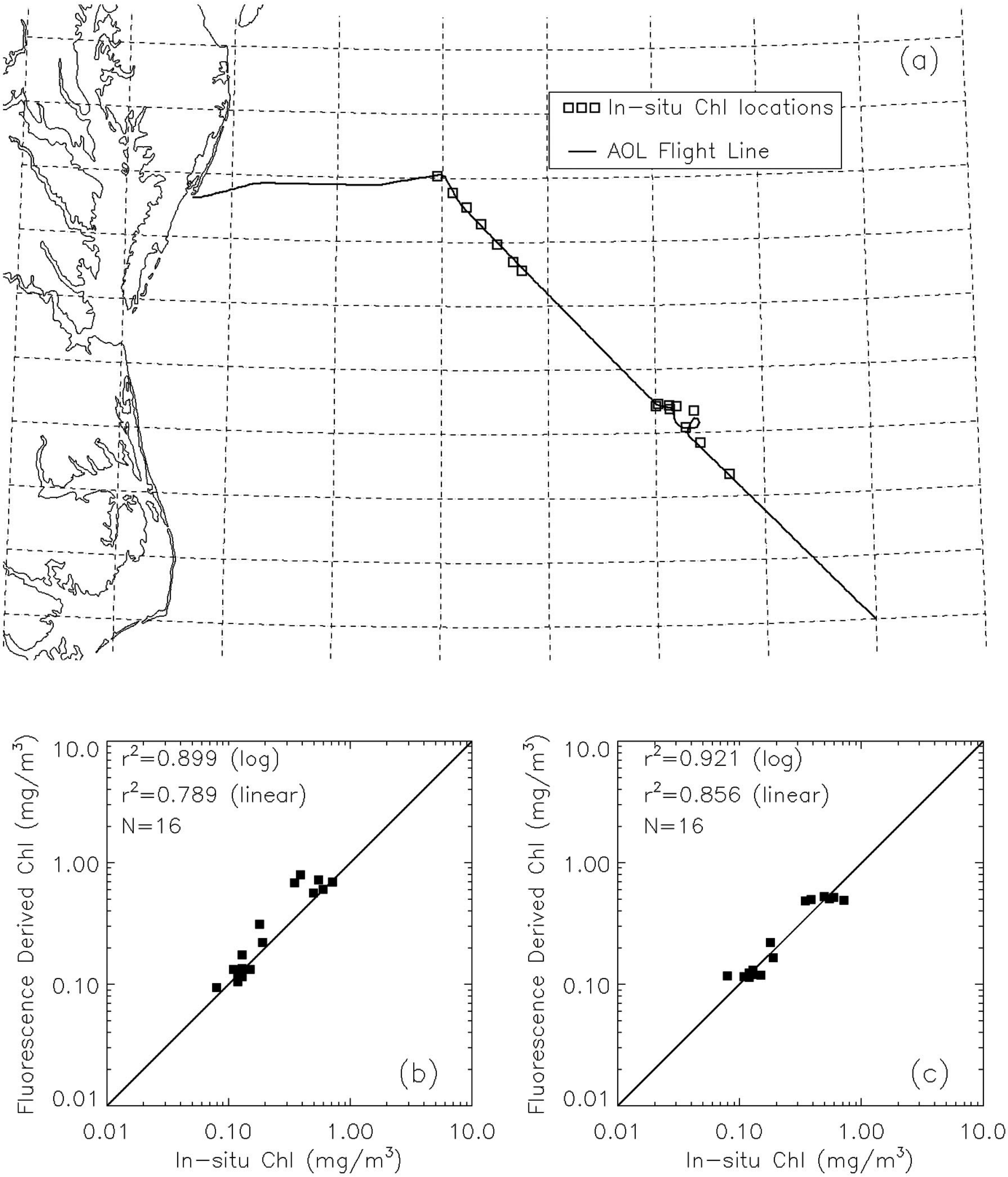

Fig. 1. Ship-based chlorophyll biomass from 3–10 May 1998 compared with airborne chlorophyll biomass retrieval using 8 May 1998 airborne laser-induced and water Raman normalized chlorophyll and CDOM fluorescence, $Chl_{F/R}$ and $CDOM_{F/R}$. (a) Location of 16 ship-derived chlorophyll biomass values (box symbol) along the Middle Atlantic Bight airborne flight line (solid line). (b) Comparison of the ship-derived chlorophyll biomass, ⟨Chl⟩, with airborne chlorophyll biomass retrieval, using airborne $Chl_{F/R}$ (but not $CDOM_{F/R}$). (c) Comparison of ship-derived chlorophyll biomass, ⟨Chl⟩, with airborne retrieval of chlorophyll biomass using both airborne $Chl_{F/R}$ and $CDOM_{F/R}$. Comparison of (b) and (c) and the regression coefficients therein shows that the use of both $Chl_{F/R}$ and $CDOM_{F/R}$ provides a more accurate retrieval than $Chl_{F/R}$ alone.

flight [as shown in Fig. 1(a)]. These ship-derived chlorophyll biomass values are compared to chlorophyll biomass retrieved by using airborne $Chl_{F/R}$ (but not $CDOM_{F/R}$) as shown in Fig. 1(b). The ship-derived chlorophyll biomass values are then compared with chlorophyll biomass retrieved by using both airborne $Chl_{F/R}$ and $CDOM_{F/R}$ as shown in Fig. 1(c). Comparison of Fig. 1(b) and 1(c) and their regression coefficients shows that a more accurate retrieval is obtained by using both $Chl_{F/R}$ and $CDOM_{F/R}$.

Second, 79 ship–derived chlorophyll values from 3–10 May 1998 [as shown in Fig. 2(a)] are compared with chlorophyll biomass values retrieved by using NASA's Shipboard Laser Fluorometer (SLF), chloro-

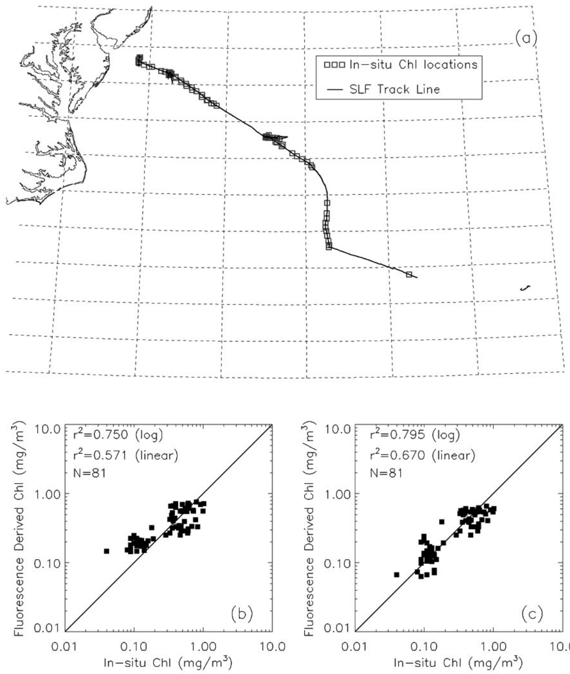

Fig. 2. Comparison of ship-based chlorophyll biomass, ⟨Chl⟩, using $Chl_{F/R}$ [from shipboard laser fluorometer (SLF)] and $CDOM_{F/R}$ (from concurrent airborne lidar). (a) Seventy-nine 3–10 May 1998 ship-based chlorophyll biomass values and coincident NASA Shipboard Laser Fluorometer (SLF) chlorophyll fluorescence, $Chl_{F/R}$. The $CDOM_{F/R}$ is obtained from contemporary 9 May 1998 airborne overflight of the AOL. (b) The ship-based chlorophyll biomass values compared with the airborne retrieved biomass values using only $Chl_{F/R}$ (but not $CDOM_{F/R}$). (c) Ship-based chlorophyll biomass values compared with the airborne retrieved biomass values using both $Chl_{F/R}$ and $CDOM_{F/R}$. Comparison of (b) and (c) and the regression coefficients therein shows that the use of both $Chl_{F/R}$ and $CDOM_{F/R}$ provides a more accurate retrieval than $Chl_{F/R}$ alone.

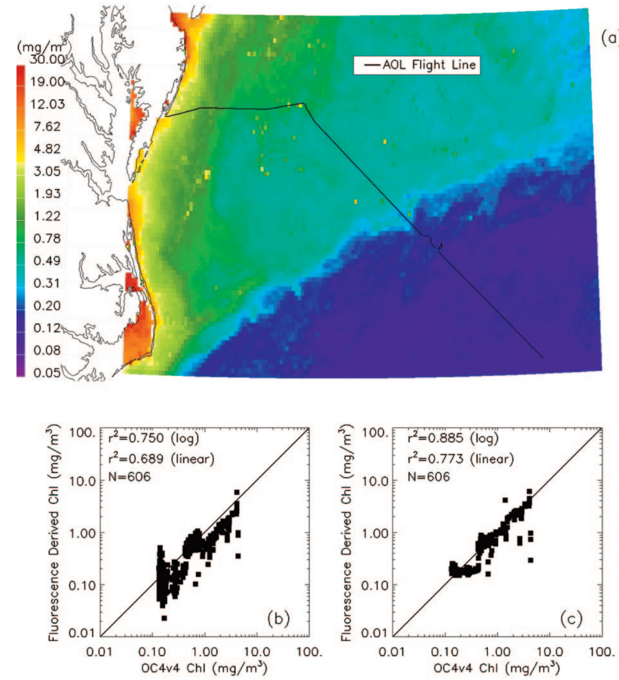

Fig. 3. Airborne lidar retrieval theory demonstration using SeaWiFS OC4v4 chlorophyll biomass data as a surrogate for shipboard-derived chlorophyll biomass. (a) Along the airborne flight line, the shipboard surrogate chlorophyll is selected from this SeaWiFS OC4v4 chlorophyll biomass image (composed of an average of 20 images taken between 2 May and 26 May 1998). (b) Comparison of the surrogate ship-based chlorophyll compared with airborne retrieval using only the 8 May 1998 airborne $Chl_{F/R}$ (and not the $CDOM_{F/R}$). (c) Comparison of the surrogate ship-based chlorophyll compared with 8 May 1998 airborne retrieval using both the airborne $Chl_{F/R}$ and $CDOM_{F/R}$. Comparison of (b) and (c) and the regression coefficients therein shows that the use of both $Chl_{F/R}$ and $CDOM_{F/R}$ results in a more accurate retrieval than $Chl_{F/R}$ alone.

phyll fluorescence for the $Chl_{F/R}$, [and $CDOM_{F/R}$ from the contemporary 9 May 1998 airborne overflight by Airborne Oceanographic Lidar (AOL)]. Initially the ship–derived chlorophyll biomass values located along the ship track are compared with chlorophyll biomass values retrieved by using only the airborne $Chl_{F/R}$ (but not $CDOM_{F/R}$), as shown in Fig. 2(b). Then, both $Chl_{F/R}$ and $CDOM_{F/R}$ are used to retrieve the chlorophyll biomass for comparison with the ship–derived chlorophyll biomass as shown in Fig. 2(c). Comparison of Fig. 2(b) and 2(c), and their regression coefficients shows that the use of both $Chl_{F/R}$ and $CDOM_{F/R}$ provides a more accurate retrieval than $Chl_{F/R}$ alone.

Third, the airborne lidar retrieval theory is demonstrated by using SeaWiFS OC4v4 chlorophyll biomass data as a surrogate for shipboard–derived chlorophyll biomass. This surrogate shipboard chlorophyll is obtained from the SeaWiFS OC4v4 chlorophyll biomass image shown in Fig. 3(a). This chlorophyll image has an average of 20 images taken between 2 May and 26 May 1998. There are 606 satellite-derived surrogate shipboard chlorophyll values contemporaneous with the airborne overflight of the AOL. These 606 shipboard chlorophyll biomass values are first compared with chlorophyll biomass retrieved by using only the 8 May 1998 airborne $Chl_{F/R}$ as shown in Fig. 3(b). Then, these 606 shipboard chlorophyll biomass values are compared with chlorophyll biomass retrieved by using both the 8 May 1998 airborne $Chl_{F/R}$ and $CDOM_{F/R}$ as shown in Fig. 3(b). Comparison of Figs. 3(b) and 3(c) and their regression coefficients shows again that the use of both $Chl_{F/R}$ and $CDOM_{F/R}$ results in better retrievals than $Chl_{F/R}$ alone.

Fourth, the airborne lidar retrieval theory is demonstrated using only SeaWiFS data as surrogates: (a) the shipboard biomass surrogate is represented by the SeaWiFS OC4v4 chlorophyll biomass product (as in the third item above) while (b) the airborne $Chl_{F/R}$ and $CDOM_{F/R}$ surrogates are furnished by the SeaWiFS-retrieved[14] a_{ph} and a_{CDOM} inherent optical properties (IOP), respectively. The entire SeaWiFS image is used for this demonstration. Specifically, for the 2–26 May 1998 SeaWiFS composite OC4v4 chlorophyll image [see Fig. 3(a)]. Fig. 4(a) shows a regression of all 12,031 values of the standard OC4v4

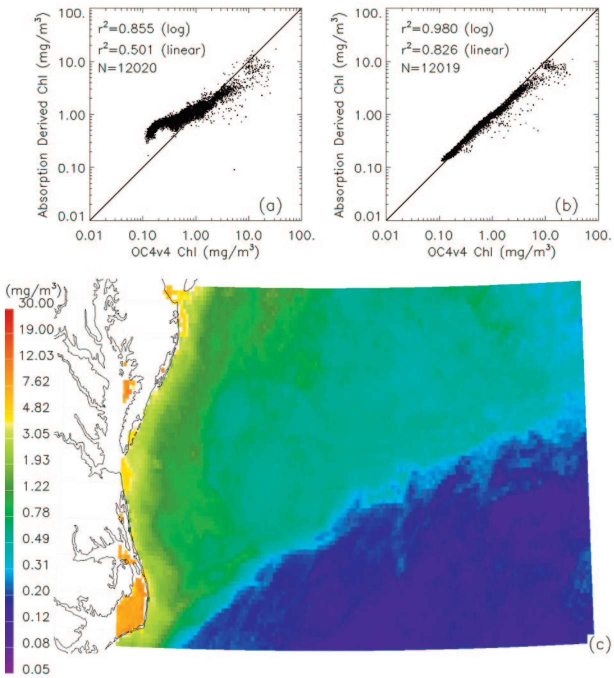

Fig. 4. Demonstration of airborne lidar chlorophyll biomass retrieval theory using only the 2–26 May 1998 SeaWiFS composite data as airborne lidar surrogates. (a) Airborne chlorophyll biomass retrieval using only the $\mathrm{Chl}_{F/R}$ surrogates (12,031 SeaWiFS retrieved a_{ph} IOP values) regressed against the shipboard biomass surrogates (12,031 SeaWiFS OC4v4 chlorophyll values). (b) Airborne chlorophyll biomass retrieval using surrogates for both the airborne $\mathrm{Chl}_{F/R}$ and $\mathrm{CDOM}_{F/R}$ (the SeaWiFS retrieved a_{ph} and a_{CDOM}) regressed against the shipboard biomass surrogates (SeaWiFS OC4v4 chlorophyll product). Comparison of (a) and (b) shows an improved retrieval when both $\mathrm{Chl}_{F/R}$ and $\mathrm{CDOM}_{F/R}$ are used.

SeaWiFS chlorophyll biomass product (serving as shipboard chlorophyll surrogates) versus airborne chlorophyll biomass retrieved from only $\mathrm{Chl}_{F/R}$ (derived from the SeaWiFS a_{ph} surrogate). Figure 4(b) shows an improved regression that uses both $\mathrm{Chl}_{F/R}$ and $\mathrm{CDOM}_{F/R}$ (respectively, derived from SeaWiFS IOP surrogates a_{ph} and a_{CDOM}). Since only SeaWiFS data is used in this latter demonstration of the airborne lidar retrieval method, other global regions were also tested with comparable results (not shown). In addition to demonstration of the airborne lidar retrieval theory, these latter results also suggest the validity of the satellite IOP-based chlorophyll biomass retrieval algorithm.[16] In fact, when 2,082 globally distributed ship–derived chlorophyll biomass values are used, the IOP-based retrieval is very comparable with the standard OC4v4 SeaWiFS biomass algorithm.[16]

4. Summary and Discussion

Chlorophyll biomass, ⟨Chl⟩, retrieval by airborne laser-induced chlorophyll fluorescence has a three-decade history with water Raman normalization in 1981 as the principal improvement during the period. Historically, only the chlorophyll fluorescence-to-Raman ratio, $\mathrm{Chl}_{F/R}$, has been used for the retrieval of chlorophyll biomass; i.e., typically after a lidar system has been vicariously calibrated by overflight of a ship cruise having chlorophyll biomass extractions, the lidar $\mathrm{Chl}_{F/R}$ can then be used during that field mission and on subsequent missions even months or years later to provide wide area biomass spatial variability mapping. The lidar-derived biomass is obtained by scale and offset regression against the original ship-based biomass truth. The principal requirement is that the relative lidar receiver channel-to-channel calibration between the ~683-nm chlorophyll fluorescence emission band and the water Raman band be maintained by periodically viewing a calibration source.

For the past decade it has been known that $\mathrm{CDOM}_{F/R}$ is highly correlated with the CDOM absorption coefficient a_{CDOM}.[12,13,14,15] Likewise during the past eight years it has been known that $\mathrm{Chl}_{F/R}$ is actually a robust surrogate for the phytoplankton absorption coefficient, a_{ph}. During very recent unpublished analyses of our lidar data it was found that ship truth chlorophyll biomass is more correlated with lidar $\mathrm{Chl}_{F/R}$ and $\mathrm{CDOM}_{F/R}$ than with $\mathrm{Chl}_{F/R}$ alone. This latter finding is in agreement with DeGrandpre *et al.*,[17] who found that ⟨Chl⟩ retrieved by reflectance ratios is more correlated with a_{ph} and a_{CDOM} than to a_{ph} alone. These findings led to the lidar biomass algorithm provided in Eqs. (1)–(6), and validation shown in Figs. 1–4, by using ship, airborne lidar, and satellite data. Use of this new theory requires that the relative lidar receiver channel-to-channel calibration between the chlorophyll fluorescence band and its water Raman band, as well as the CDOM fluorescence band and its Raman band, be maintained by calibration.

Since the number of ship-based chlorophyll values is naturally limited, chlorophyll values from a contemporaneous SeaWiFS overflight were used as surrogates for ship based chlorophyll. These SeaWiFS chlorophyll values provided additional validation of the lidar retrieval method; i.e., SeaWiFS a_{ph} and a_{CDOM} values (derived by linear inversion of a radiative transfer model[14]) were used as surrogates for the lidar $\mathrm{Chl}_{F/R}$ and $\mathrm{CDOM}_{F/R}$ and were used to retrieve the standard SeaWiFS OC4v4 chlorophyll biomass. These IOP-based retrievals compared well with the empirical OC4v4 reflectance ratio chlorophyll biomass retrievals. This comparison provides strong evidence for the validity of the lidar retrieval theory. Additionally, it suggests the validity of the global IOP-based chlorophyll biomass algorithm.[16] An IOP-based chlorophyll biomass algorithm is a powerful tool that would potentially allow (1) adjustment or tuning to match the environmental conditions of individual oceanic regions and (2) inclusion of phytoplankton photoacclimation effects, (3) phytoplankton community structure, or (4) any known absorption IOP effect.[16]

Additional work remains. To provide more confidence and confirmatory data, the retrieval method will be tested over additional ship cruises in other water masses. Too, phytoplankton species, cell size and chlorophyll content per cell should be measured to allow investigation of *in situ* biological effects associated with in-water attenuation, especially CDOM absorption (and perhaps even CDOM fluorescence emission).

The results herein and the results of others[17,18] suggest that elevated chlorophyll biomass production is associated with elevated CDOM waters. This suggests possible enhanced chlorophyll biomass production affiliated with CDOM presence. (The reverse effect, the production of CDOM by chlorophyll bearing phytoplankton, is not expected based on recent research).[21–23] Several possibilities will be investigated in future research: (a) CDOM absorption-induced photoacclimation that reduces the incident cellular irradiance, thereby enabling an increase in chlorophyll per cell,[24] (potentially through increases in photosynthetic unit (PSU) size and PSU numbers)[25]; (b) elevated pigment due to unexplained phenomena closely associated with CDOM; (c) intracellular utilization of DOM leading to increased biomass; and (d) improved global oceanic retrieval of phytoplankton primary production.

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