# The proof-of-concept vicarious calibration of SeaWiFS using a sea surface reflectance model

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## 1. INTRODUCTION

Recent advances in global climate and productivity research demonstrate a critical need for long-term ocean color satellite data records of consistent high quality. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) has supplied the oceanographic community a continuous, global marine bio-optical data set since late 1997. The community relies heavily on its data products, the concentration of the phytoplankton pigment chlorophyll *a*, $C_a$, in particular, to support studies ranging from management of regional ecosystems to development of decadal climate records. The utility of SeaWiFS results, in part, from its rigorous, mission-long on-orbit vicarious calibration, executed by the NASA Ocean Biology Processing Group (OBPG) to regulate the instrument-atmospheric correction system. In this calibration, top-of-atmosphere visible radiances are adjusted using *in situ* normalized water-leaving radiances, $L_{wn}(\lambda)$. Unfortunately, well-characterized time series of *in situ* radiometric data are scarce in the eras of the SeaWiFS predecessors, in particular, the NASA Coastal Zone Color Scanner (CZCS) and the JAXA Ocean Color and Temperature Scanner (OCTS). Recently developed sea surface reflectance models (SSRM), however, accurately reproduce radiance spectra observed in the field, at least for clear, marine waters. Simplifications to the radiative transfer equation permit the estimation of $L_{wn}(\lambda)$ via a single input parameter, $C_a$, a measurement for which long-term, seasonal *in situ* time series exist. Here, we illustrate the efficacy of a seasonally varying SSRM for the temporally independent vicarious calibration of SeaWiFS. Modeled gains are statistically compared with those calculated using data from the Marine Optical Buoy (MOBY) and Level-2 validation results are presented. We propose that refinement of these techniques will provide a viable mechanism for the retrospective vicarious calibration of CZCS and OCTS.

## 2. MODEL DEVELOPMENT

In clear marine waters, subsurface *R* is regularly described as a function of marine inherent optical properties via $R = f\, b_b\, (a + b_b)^{-1}$, where *f* is dimensionless term that varies with water composition, sea state, and illumination conditions. Table 1 provides parameter definitions and units, and spectral dependence is implied. The remote-sensing relevant term $L_{wn}$ may be subsequently calculated from *R* via:

$$L_{wn} = \frac{t_u\, t_d}{n^2}\, F_0\, \frac{f}{Q}\, \frac{b_b}{a}$$

The sea surface reflectance algorithm of Morel and Maritorena (2001; MM01) and the bi-directional reflectance parameterizations of Morel et al. (2002) permit the estimation of the unknown spectrally dependent variables in this equation, *a*, $b_b$, *f*, and *Q*, via a single geophysical input, $C_a$. Following, knowledge of $C_a$ in a given *Case-1* location (phytoplankton being the only optically significant constituent) provides sufficient information to estimate $L_{wn}$ at that location.

| | | | |
|---|---|---|---|
| $a$ | absorption coefficient ($m^{-1}$) | $\mu_d$ | mean cosine for downward flux |
| $b_b$ | backscattering coefficient ($m^{-1}$) | $n$ | refractive index of seawater (unitless) |
| $F_0$ | mean extraterrestrial solar irradiance ($\mu W\ cm^{-1}\ nm^{-1}$) | $Q$ | bi-directional reflectance function ($= E_u/L_u$; $sr^{-1}$) |
| $K_d$ | downwelling diffuse attenuation coefficient ($m^{-1}$) | $R$ | reflectance ($= E_u/E_d$; unitless) |
| $L_{wn}$ | normalized water-leaving radiance ($\mu W\ cm^{-1}\ nm^{-1}\ sr^{-1}$) | $t_d$ | downward irradiance air-sea transmittance (unitless) |
| | | $t_u$ | upward radiance air-sea transmittance (unitless) |

Table 1. Parameter definitions and units.

$b_b$ is estimated from $C_a$ using the empirical relationships of Loisel and Morel (1998) and MM01. The relationship $\mu_d K_d$ is used as a proxy for *a*, as $K_d$ encompasses the effects of all absorbing material in the water column and specific $C_a$-based functions for dissolved and detrital absorption possess significant uncertainties. $\mu_d$ and $K_d$ are estimated from $C_a$ following Morel and Loisel (1998) and MM01, respectively. Both *f* and *Q* are acquired via the equations and tables provided in Appendix B of Morel et al. (2002). As the above are strictly *Case-1* relations, the utility of the SSRM degrades significantly in the presence of optically relevant nonalgal material.

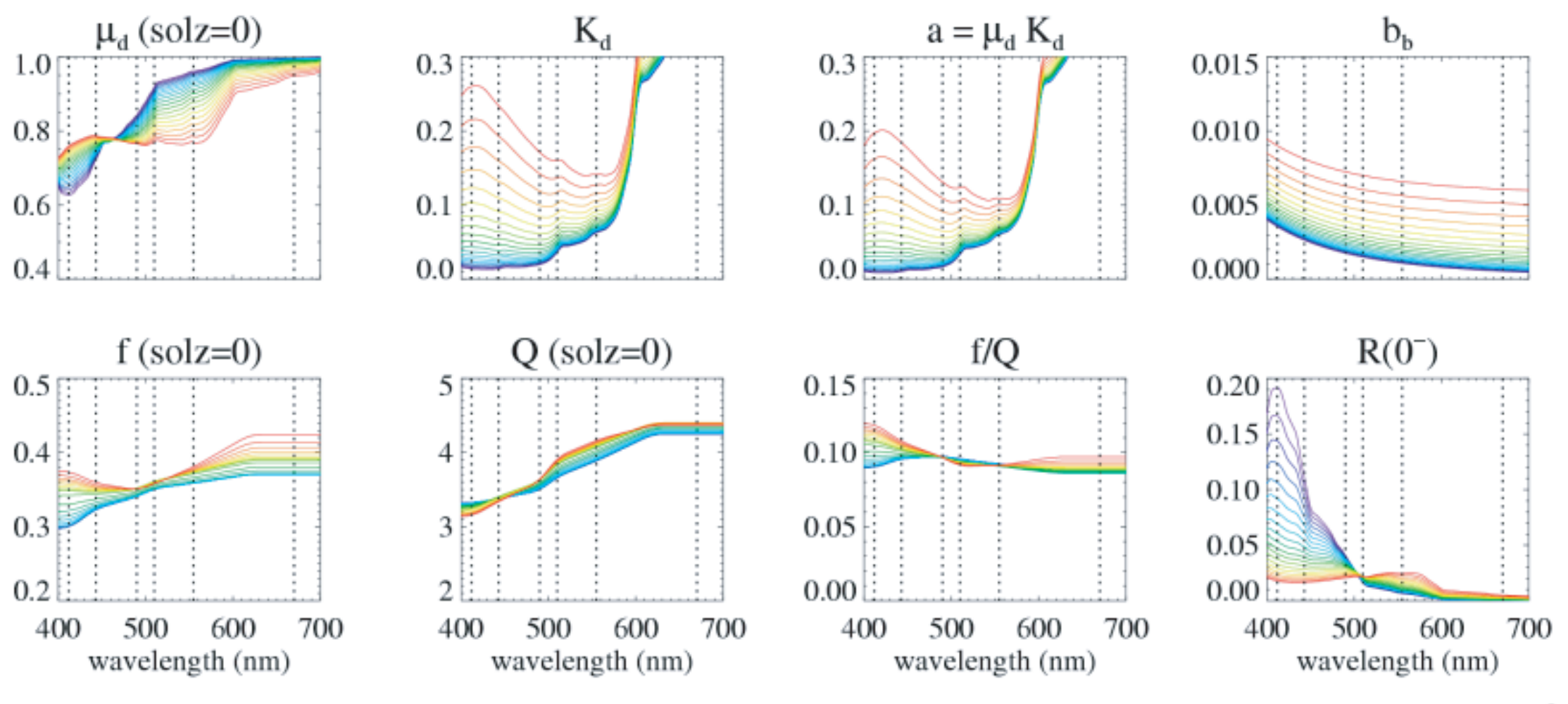

Figure 1

Above, we illustrate the dynamic range of the $C_a$-based SSRM model parameters. SeaWiFS center wavelengths are indicated by vertical dashed lines. Note the limited range of *R* in the blue-green (490-nm) and green (510 and 555-nm) wavelengths.

## 3. MODEL EVALUATION

We evaluated both the sensitivity of the SSRM to $C_a$ and the ability of the SSRM to reproduce $L_{wn}$ observed in the field. For the former, $C_a$ at three concentrations was varied sequentially by 33 and 67%. Corresponding changes of 20 and 70% in *R* were typical, respectively, most notably for the blue and red regions of the spectrum. The lower plots emphasize the limited dynamic range of 490 and 510-nm. Note also the consistent spectral shape of the differences over approximately two orders of magnitude of $C_a$.

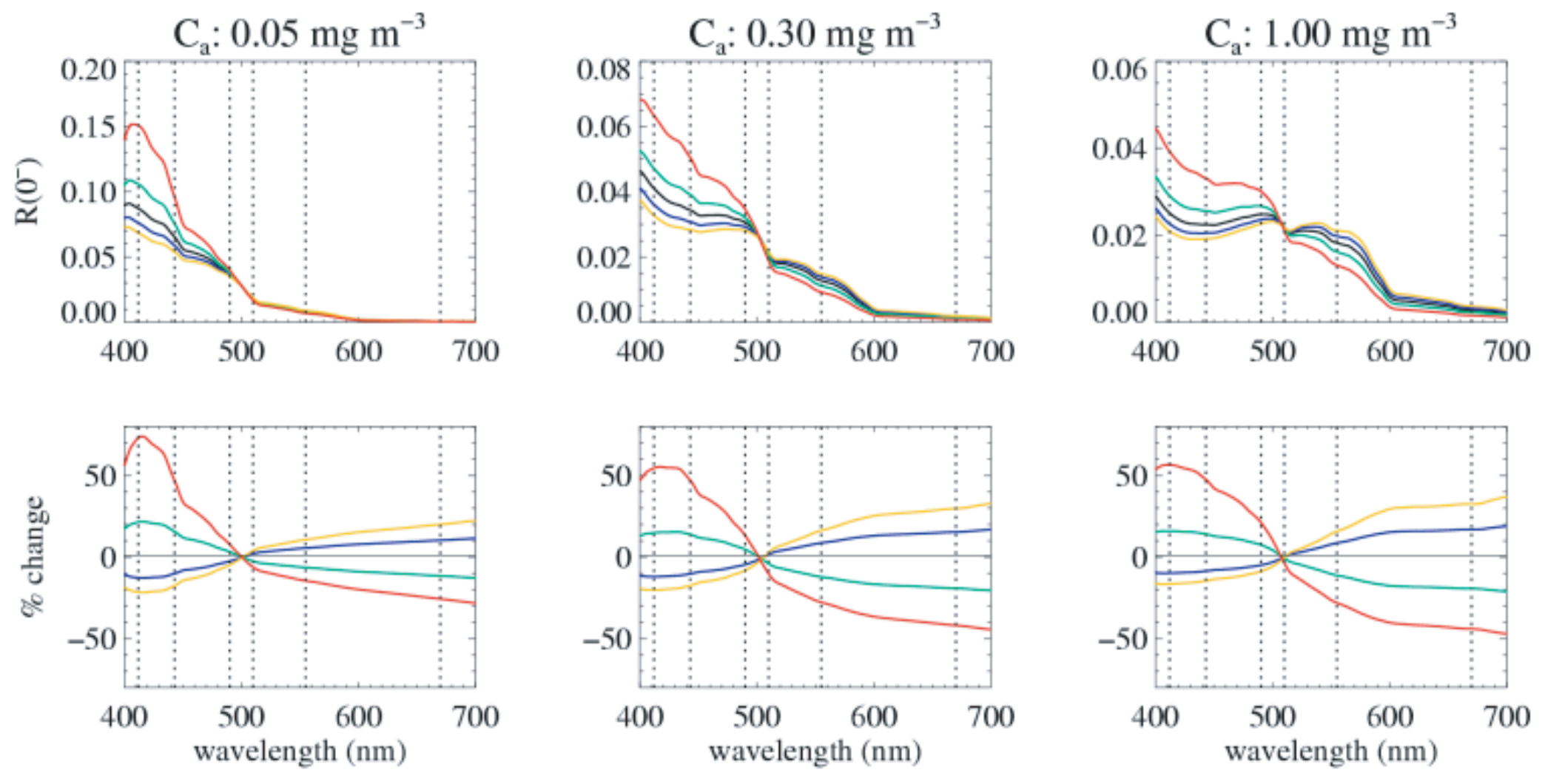

Figure 2

The SSRM was further evaluated using *in situ* data from the first eight Atlantic Meridional Transect (AMT) campaigns. To ensure this analysis was conducted using predominantly *Case-1* conditions, field data were limited to those with $C_a < 0.3$ mg m$^{-3}$ and water depths > 1000 meters. Radiometrically-modeled $C_a$ (OC4v4; O'Reilly et al. 2000) were used as input into the SSRM. OC4v4, the standard SeaWiFS $C_a$ algorithm, has been well validated for these data (Hooker and McClain 2000) and its use in lieu of *in situ* $C_a$ eliminates the uncertainty of the additional measurements, while ensuring optical consistency within the analysis. While the results are encouraging for the blue wavelengths, the SSRM consistently underestimates $L_{wn}(490)$ and $L_{wn}(555)$, again highlighting the limited dynamic range of this spectral region.

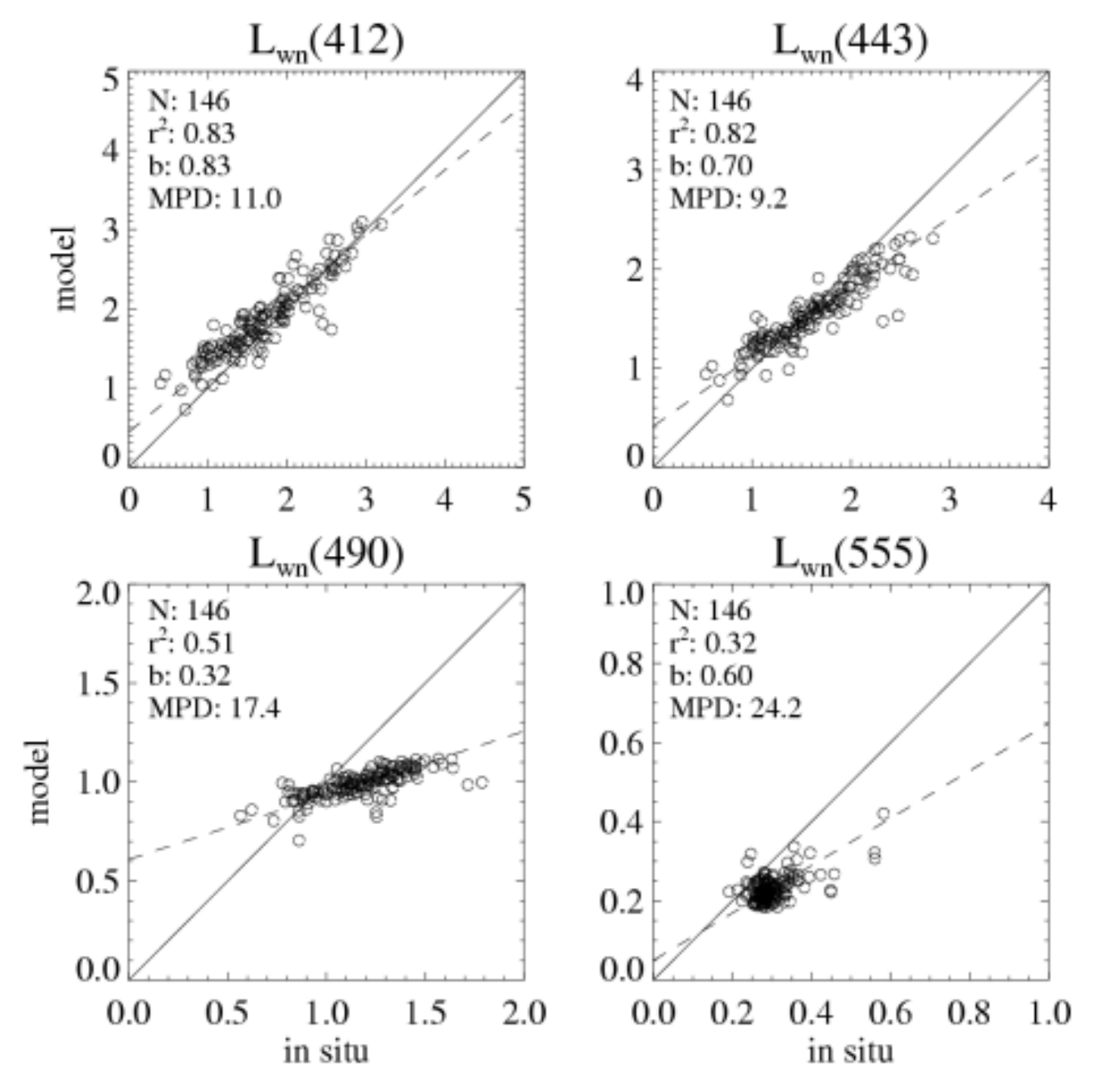

Figure 3A. The abbreviations *b* and *MPD* indicate slope and median absolute percent difference, respectively.

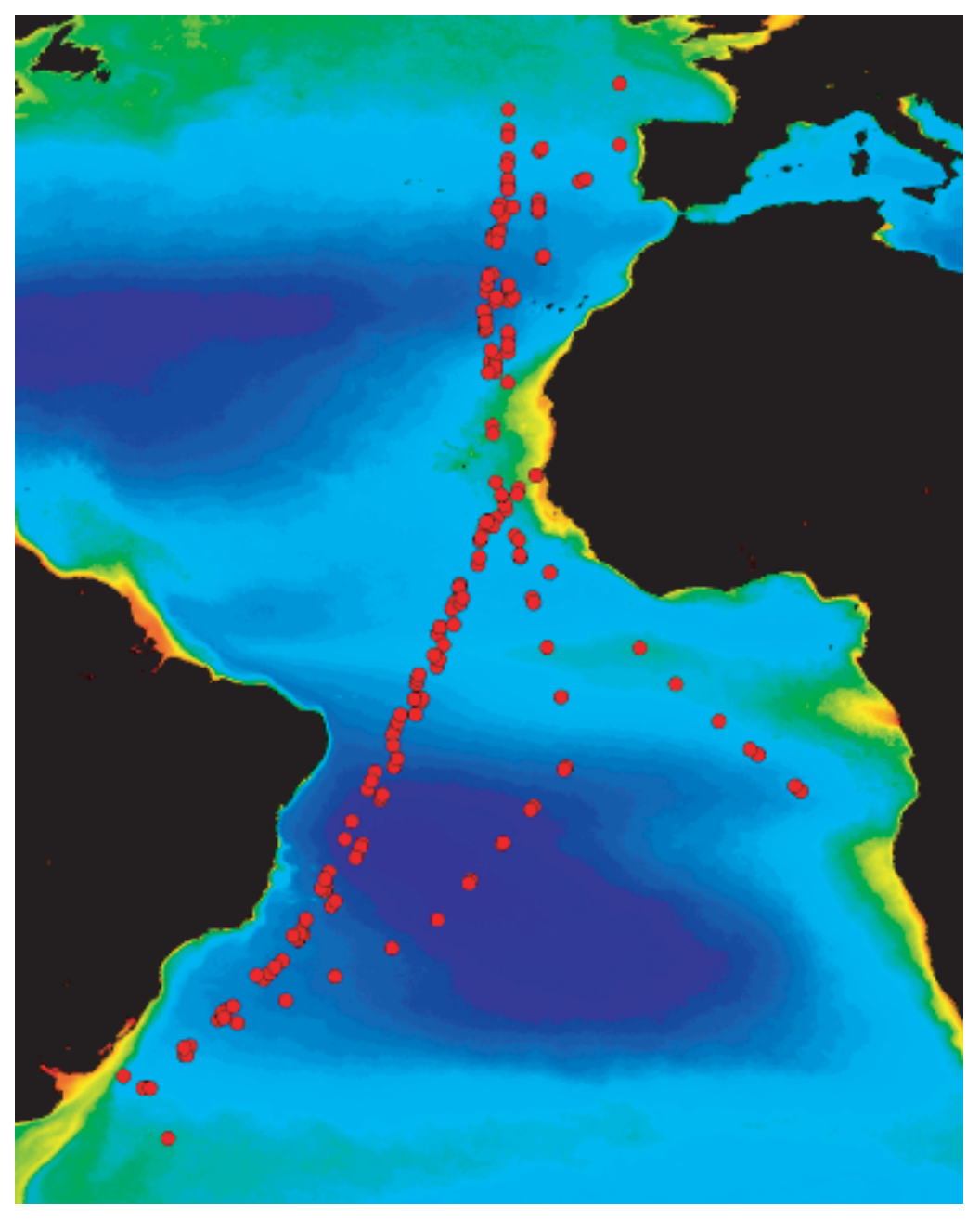

Figure 3B. AMT 1-8 stations. Data courtesy S. Hooker (NASA) & co-PI's.

## 4. $C_a$ CLIMATOLOGIES

For the SSRM-based vicarious calibration of SeaWiFS, we require candidate study sites to:

(1) be in a location where SeaWiFS acquires regular LAC (1.1 km² at nadir) coverage
(2) be considered *Case-1*
(3) have a well-characterized, annual *in situ* $C_a$ time series

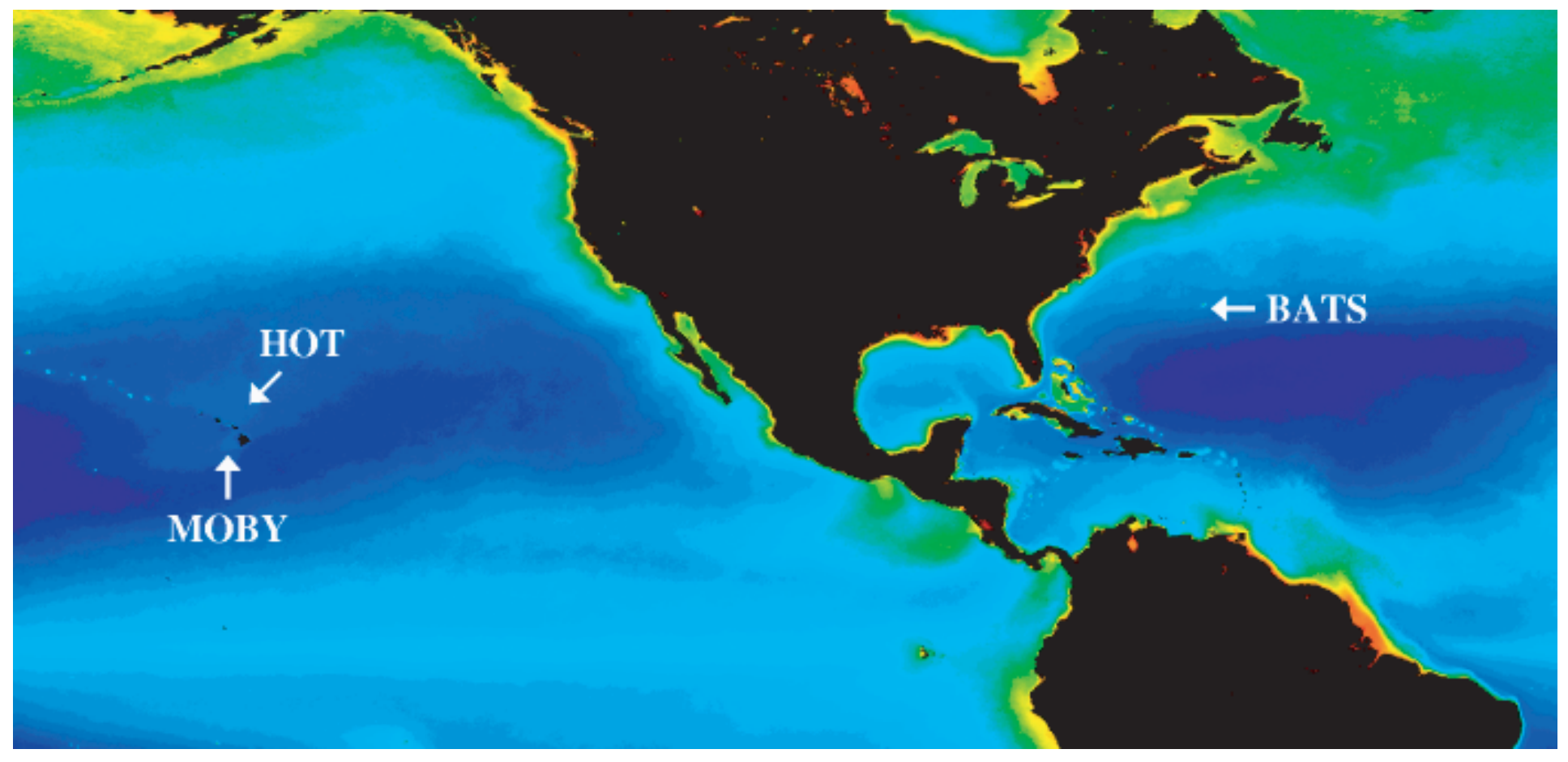

Figure 4A

The Hawaiian Ocean Time-series (HOT; Karl and Lukas 1996) Station ALOHA and Bermuda Atlantic Time-series Study (BATS; Michaels and Knap 1996) provide fluorometrically-derived $C_a$ data sets that satisfy all of these criteria. Although results are not presented here, we also considered regional time series developed using SeaWiFS Level-3 monthly bin files.

Only 6% of input *in situ* stations result in valid vicarious calibration match-ups. To increase the input sample size, we generated generic climatological expressions for the $C_a$ data. A quadratic fit was calculated to express $C_a$ as a function of day of year. Using this expression and the SSRM, we estimated SeaWiFS-specific $L_{wn}$ for every day of 1998 - 2004 at both Station ALOHA and the BATS site. These spectra were subsequently input into the OBPG vicarious calibration system (Eplee et al. 2001) and vicarious gains, *g*, were derived.

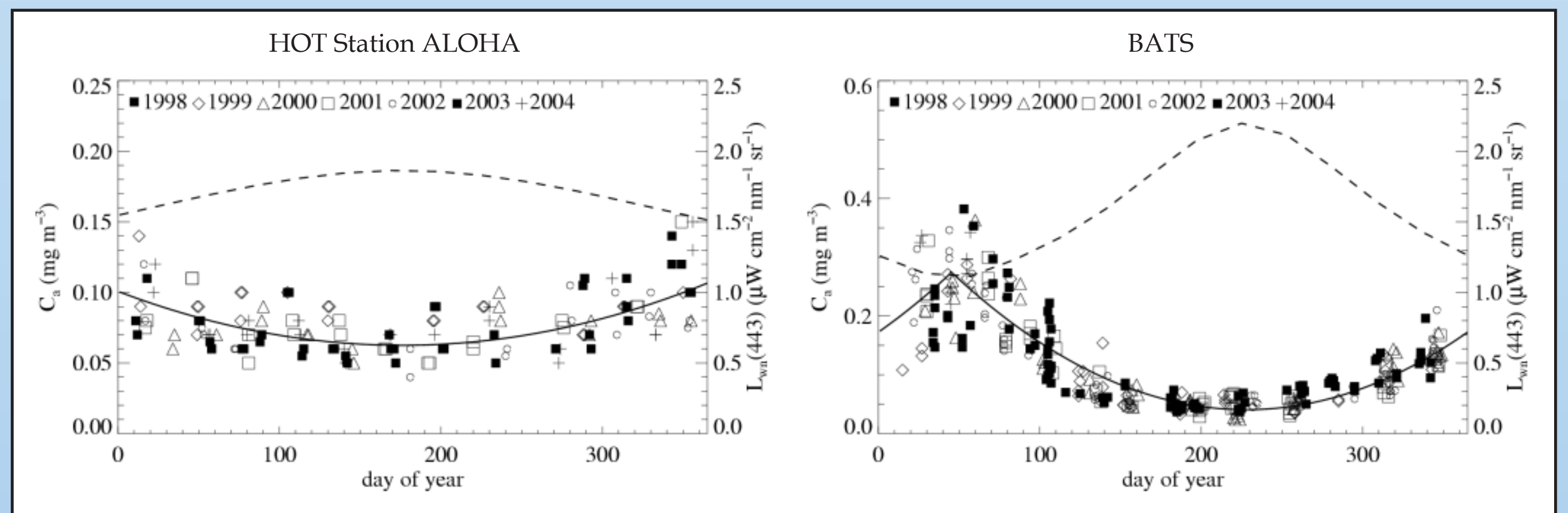

Figure 5. The statistically-derived $C_a$ climatologies (solid line), *in situ* $C_a$ (symbols), and resultant SSRM $L_{wn}(443)$ (dashed line).

## 5. VICARIOUS CALIBRATION & VALIDATION

With the exception of 490 and 510-nm, the SSRM and MOBY gains ($g_s$ and $g_m$, respectively) agree to within 1%. As the atmosphere contributes a major portion of the radiance measured at the sensor (~90%), however, changes of this magnitude are considerable (~10%) with respect to $L_{wn}$, as indicated the $R_{rs}(443)$ validation results presented in Figure 6.

| | N | 412 | 443 | 490 | 510 | 555 | 670 |
|---|---|---|---|---|---|---|---|
| MOBY | 55 | 1.0336 | 1.0091 | 0.9887 | 0.9947 | 0.9958 | 0.9645 |
| HOT | 22 | 1.0363 | 1.0099 | 0.9771 | 0.9821 | 0.9886 | 0.9654 |
| BATS | 16 | 1.0389 | 1.0009 | 0.9731 | 0.9809 | 0.9899 | 0.9648 |
| HOT + BATS | 38 | 1.0374 | 1.0061 | 0.9753 | 0.9815 | 0.9892 | 0.9652 |
| % difference | | 0.37 | -0.30 | -1.36 | -1.33 | -0.66 | 0.07 |

Table 2. Comparison of MOBY-derived gains ($g_m$) with those from the SSRM ($g_s$).
The *% difference* was calculated as 100% * ("HOT + BATS" - MOBY) / MOBY.

Within the context of CZCS and OCTS reprocessing, however - the generation of decadal $C_a$ records - the absolute radiometric calibration is less significant provided the derived $C_a$ is without statistical bias. Given the form of OC4v4 and the spectral dependence of the differences, the impact of using $g_s$ is a predictable increase in $C_a$. $C_a$ validation with $g_m$ indicates excellent agreement for oligotrophic conditions ($C_a < 0.1$ mg m$^{-3}$), but a slight negative bias for the mesotrophic and eutrophic regimes. In contrast, $C_a$ validation with $g_s$ yields excellent agreement for all regimes. Both agree well near the annual global average of 0.25 mg m$^{-3}$ and both produce similar, reasonable statistical results. As before, only stations with water depths > 1000 meters were considered.

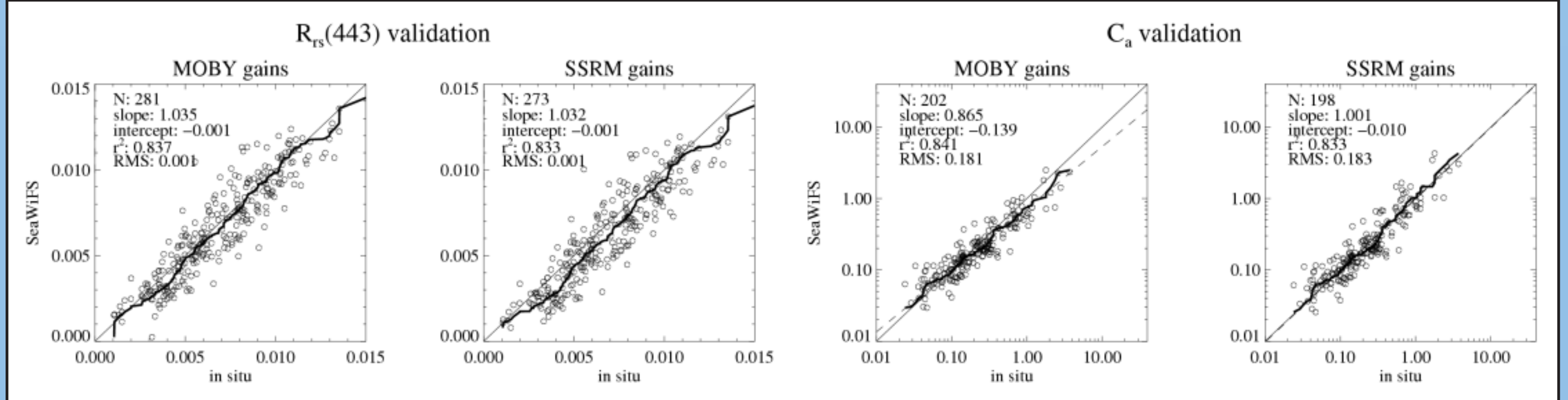

Figure 6. Comparisons of *in situ* and satellite-derived products for SeaWiFS data processed using $g_m$ and $g_s$. The bold solid lines show quantile-quantile comparisons, where sorted (ascending order) data are compared. Methods described in Bailey and Werdell (2006).

## 6. ACKNOWLEDGEMENTS & REFERENCES

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