EVALUATION OF INSTRUMENT SELF-SHADING AND ENVIRONMENTAL ERRORS ON OCEAN COLOR ALGORITHMS

Mati Kahru and B. Greg Mitchell
Scripps Institution of Oceanography, La Jolla, CA 92093-0218, USA
E-mail: mkahru@ucsd.edu, gmitchell@ucsd.edu

ABSTRACT

Upwelling radiance measured by an in-water instrument of a finite size is decreased by the instrument's own shadow. The ocean optics protocols for SeaWiFS validation [*Mueller and Austin*, 1995] recommend applying the self-shading correction of *Gordon and Ding* [1992]. In practice, however, the self-shading correction has been seldom used and the SeaWiFS chlorophyll *a* (chl *a*) algorithms were developed without the correction [*O'Reilly et al.*, 1998]. We evaluate the effect of the self-shading correction on our CalCOFI bio-optical data set with the chl *a* range of 0.05-32.5 mg m^{-3}. We show that at 443 nm the error in the normalized water-leaving radiance L_{WN} (or remote sensing reflectance R_{rs}) induced by omitting the self-shading correction is usually below 5% at chl *a* below 1 mg m^{-3} but increases to about 30% at our highest chl *a* level. The influence of the self-shading correction is reduced to a half when ratios of L_{WN} (443) or L_{WN} (490) to L_{WN} (555) are used. We also evaluate the errors due to small-scale spatial and temporal variability of the estimates of the upwelling radiance (L_u), downwelling irradiance (E_d), remote sensing reflectance (R_{rs}) and R_{rs} ratios. We do this using data from multiple casts at the same location. We show that in ideal surface conditions (calm sea surface, low wind) the relative error in L_u and E_d measurements is approximately 10%. The error of estimating R_{rs} is reduced to about 5% due to taking the ratio of L_u to E_d, and the relative error of the ratio of R_{rs} (490)/R_{rs} (555) is further reduced to about 4%.

INTRODUCTION

Algorithm development and validation for SeaWiFS and other ocean color sensors require data sets of high-quality bio-optical measurements. The ocean optics protocols for SeaWiFS validation have been compiled by *Mueller and Austin* [1995]. Some of the recommendations of the protocols, however, have been seldom used.

The operational SeaWiFS chlorophyll *a* (chl *a*) algorithm [*O'Reilly et al.*, 1998] is based on the SeaBAM data set of 919 bio-optical measurements. The SeaBAM data set was not corrected for instrument self-shading. It is well known that the upwelling radiance (L_u) measured by an in-water instrument of a finite size is affected by the instrument's own shadow. As shown by theoretical calculations [*Gordon and Ding*, 1992] and measurements [*Zibordi and Ferrari*, 1994], this error can be corrected if the product of the total absorption coefficient times the radius of the instrument is below a certain limit. About one-third of the SeaBAM data set originated from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) bio-optics program [*Mitchell and Kahru*, 1998]. We evaluate the influence of the self-shading correction on the estimates of the normalized water-leaving radiances (L_{WN}) and ratios of L_{WN} of the

CalCOFI data set. The errors in estimates of the remote sensing reflectance (R_{rs}) and R_{rs} ratios, respectively, are equivalent.

Satellite sensors (e.g. SeaWiFS) and in-water bio-optical sensors take measurements at very different spatial scales. Whereas the measurement spot of the satellite sensor is an area of approximately 1 km^2, the in-water sensor measures at much smaller spatial scales. The small-scale spatial and temporal variability may be an important issue when comparing *in situ* and satellite measurements. We compared the small-scale variability of in-water optical measurements by analyzing multiple casts taken at the same location.

METHODS AND DATA

Vertical profiles of downwelling spectral irradiance and upwelling radiance were measured with underwater radiometers MER-2040 and MER-2048 (Biospherical Instruments Inc.). Details of the data collection and processing are given in *Mitchell and Kahru* [1998] and *Kahru and Mitchell* [1998]. Since the submission of the CalCOFI data set to SeaBAM several improvements were made to the CalCOFI bio-optical data set. First, more data were added, including data from a massive red tide event [*Kahru and Mitchell*, 1998], increasing the total number of measurements collected between August, 1993 and April, 1998 to 461. Second, improved procedures of handling the data were implemented. Instrument self-shading correction [*Gordon and Ding*, 1992] was implemented according to SeaWiFS protocols [*Mueller and Austin*, 1995; *Kahru and Mitchell*, 1998]. The total absorption coefficient $a(\lambda)$ was estimated as $0.7 * K_{Ed}(\lambda)$, where 0.7 is the mean cosine of the radiance field for the upper ocean and $K_{Ed}(\lambda)$ is the vertical attenuation coefficient for downwelled irradiance . The estimate of the mean cosine is based on our measurements and is consistent with theoretical calculations [*Kirk*, 1991]. The radius of the MER-2040 body is 10.5 cm. Other attached sensors, weights, cables and frame of the profiling package increase the effective shadow. To compensate for that, the effective radius was assumed to be 15 cm. The ratio of the diffuse skylight to direct sunlight was assumed to be 0.43 for a clear sky (corresponding to 70% direct and 30% diffuse irradiance, R. Frouin, personal communication, 1997) and to 0.8 for a totally overcast sky. For a partially cloudy sky a weighting function between these two values was used.

Multiple vertical casts were taken with MER-2040 at 50 bio-optical stations in the Ross Sea as part of the JGOFS Southern Ocean study (November-December, 1997). Most of the stations had two comparable casts (down-cast and up-cast) taken within 30 minutes. Several stations had up to 6 down- and up-casts. These data were collected under near-ideal surface conditions of very calm seas and light winds. The between-cast variability of these measurements was used to calculate relative errors due to small-scale spatial and temporal variability on estimates of E_d, L_u, L_{WN}, R_{rs} and various ratios used in ocean color algorithms.

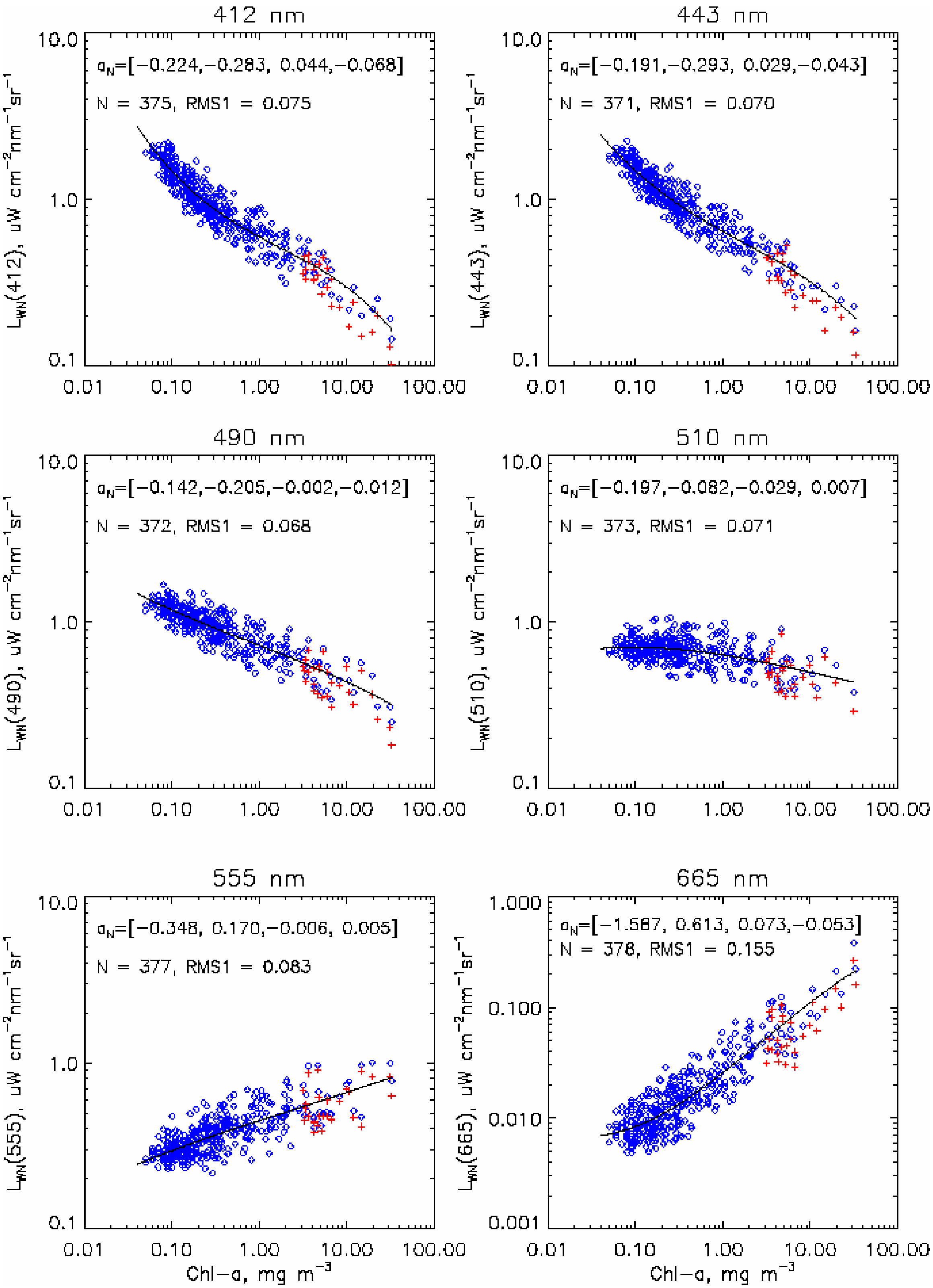

Figure 1. Normalized water-leaving radiances L_{WN} as a function of chl *a* with the self-shading correction (blue diamonds) and without (red pluses). The uncorrected data is shown only for chl *a* > 3.0. The coefficients of the cubic regression (a_0 to a_3) of the log-log relationship between L_{WN} and chl *a* (black curve) are given in the inset.

RESULTS

As expected, the influence of the instrument self-shading on estimates of L_{WN} becomes significant at high chl *a* (Figure 1). The range of chl *a* in this data set is 0.05-32.5 mg m^{-3}. L_{WN} shows a relatively consistent relationship with chl *a*. The inherent scatter is due to, among others, variable light field, surface conditions, variations in the absorption and scattering characteristics. In the log-log space the relationship can be fitted with a cubic polynomial. The non-linearity (curvature) of this relationship is more evident at shorter wavelengths (e.g. 412 nm and even more so in the UV region). L_{WN} can be calculated from the relationship $\log(L_{WN}) = a_0 + a_1 * C + a_2 * C^2 + a_3 * C^3$. The coefficients of the polynomial (a_0 to a_3) are given in Figure 1. In the log-log space the corrections seem to be minor, affecting only the high chl *a* part of the range, but they definitely influence the shape of the L_{WN} versus chl *a* relationship.

Figure 2 shows the relative errors due to omitting the self-shading correction. The error was estimated as (corrected value – uncorrected value)/corrected value. At all wavelengths except 412 and 665 nm, the relative error of L_{WN} is generally below 5% at chl *a* below 1 mg m^{-3} but increases to about 30% at our highest chl *a*. At 412 nm the error is slightly higher due to higher total absorption, especially at high chl *a*. At 665 nm the correction is usually between 15 and 20% even at low chl *a*, due to high absorption by the seawater itself.

Ocean color algorithms typically use ratios of R_{rs} or L_{WN} at different wavelengths. As the effect of self-shading is similar at different wavelengths, it is expected that taking a ratio cancels out a significant part of the self-shading effect. Indeed, on a typical scatter plot of chl *a* versus $L_{WN}(443)/L_{WN}(555)$ or $L_{WN}(490)/L_{WN}(555)$ in the log-log scale the effects of the self-shading correction are hardly noticeable (Figure 3, top). Analysis of the relative error (Figure 3, bottom) shows that taking a ratio has reduced the error by approximately a half. For chl *a* concentration below 1 mg m^{-3} the relative error due to self-shading is below 3% for $L_{WN}(490)/L_{WN}(555)$ and slightly higher for $L_{WN}(443)/L_{WN}(555)$. At our highest chl *a* of 32.5 mg m^{-3} the relative error is approximately 10% for $L_{WN}(490)/L_{WN}(555)$ and 15% for $L_{WN}(443)/L_{WN}(555)$. This is due to the lower absorption at 490 versus 443 nm, and due to more similarity between the absorption coefficients at 490 and 555 nm as compared to those at 443 and 555 nm.

Analysis of the multiple vertical casts taken within approximately 30 minutes demonstrates the effects of environmental and methodological noise under near-ideal conditions. Plots of the relative errors of L_u and E_d (Figures 4 and 5) show that for all but the 665 nm band the relative errors are approximately 10%. At 665 nm the errors are approximately 15% for L_u and 20% for E_d. For L_u the highest error is always near the surface (at 1 m) whereas for E_d the highest errors are spread out in the top 10 m (top 20 m for $E_d(555)$). The surface extrapolations $L_u(0^-,\lambda)$ and $E_d(0^-,\lambda)$ have smaller errors as they are derived by using a depth range (typically between 0 and 15 m). Calculating L_{WN} and R_{rs} involves taking a ratio of L_u and E_d, and the relative errors are therefore reduced by approximately a half. At 443 and 490 nm the relative error in R_{rs} is approximately 5% at the surface (Figure 6, top). When the typical reflectance ratios $R_{rs}(443)/R_{rs}(555)$ and $R_{rs}(490)/R_{rs}(555)$ are calculated, the relative error is reduced further, to about 4% at the surface and 2% in the surface mixed layer (Figure 6, bottom).

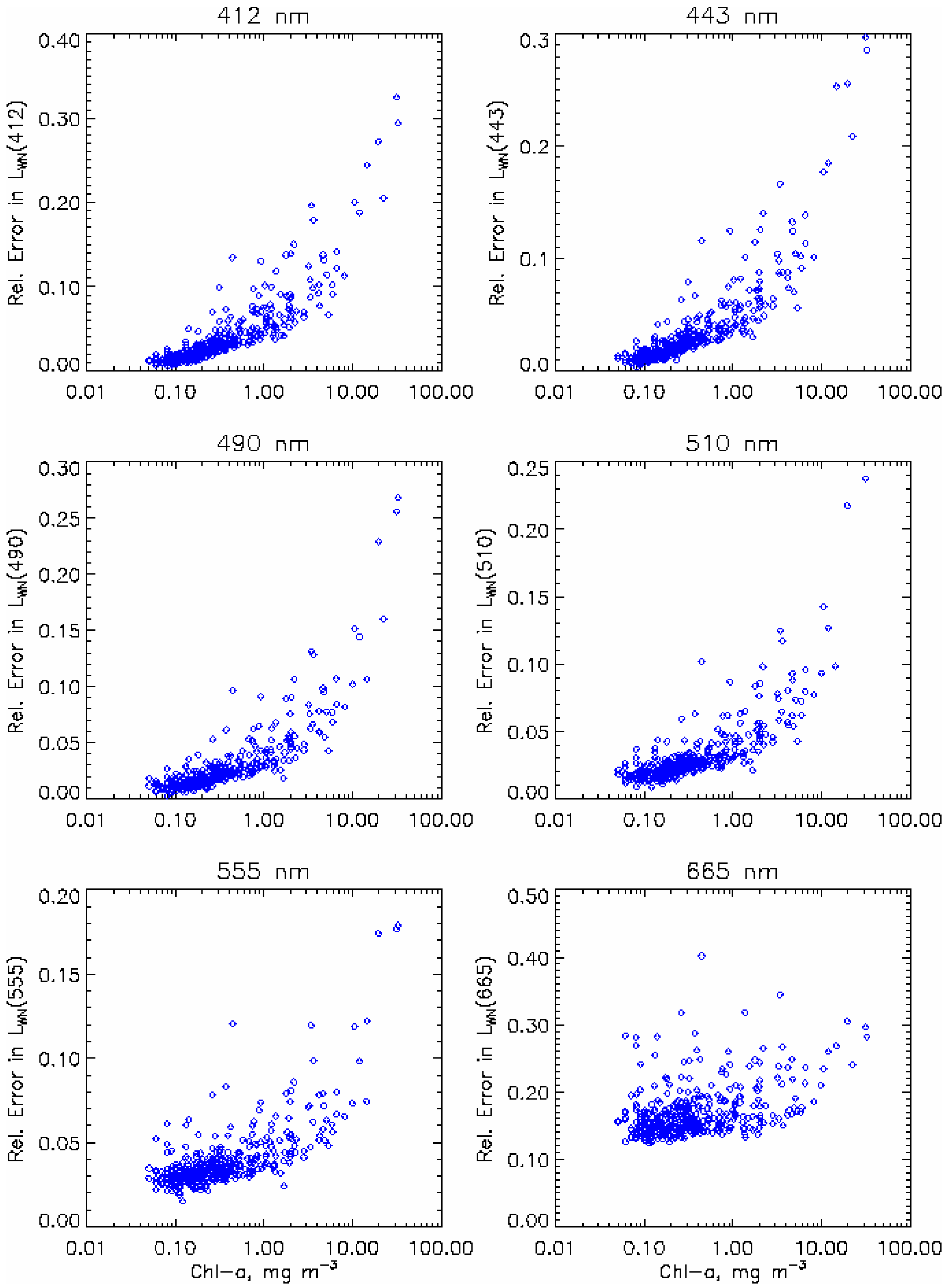

Figure 2. Relative error in the normalized water-leaving radiances L_{WN} at SeaWiFS wavelengths due to instrument self-shading as a function of chl *a*.

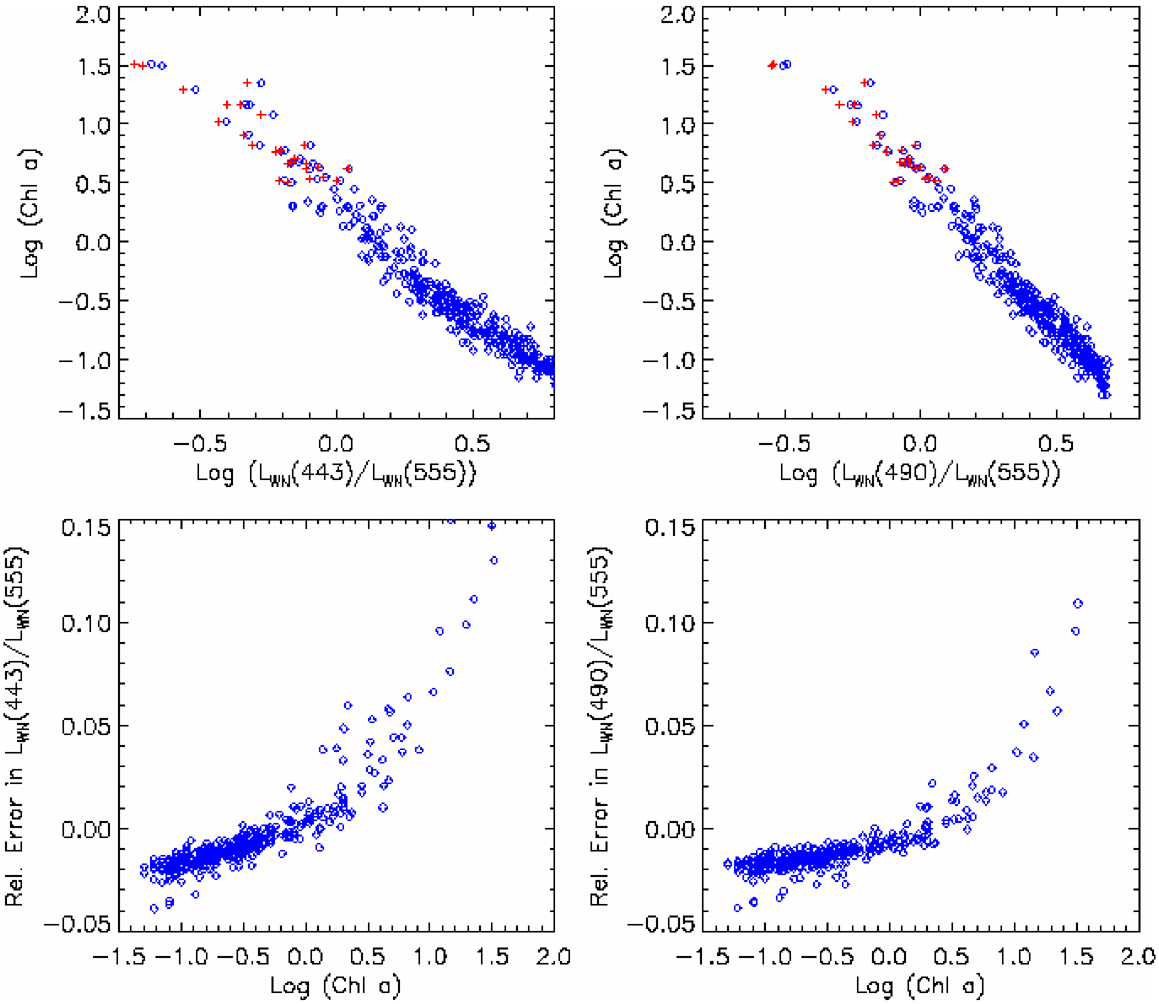

Figure 3. (top) Chl *a* as a function of the ratio of normalized water-leaving radiances L_{WN}(443)/L_{WN}(555) and L_{WN}(490)/L_{WN}(555) after correction for instrument self-shading (blue diamonds) and without the correction (red pluses). As the self-shading correction becomes significant only at higher chl *a*, only those points with chl *a* > 3.0 are shown. (bottom) Relative error in L_{WN}(443)/L_{WN}(555) and L_{WN}(490)/L_{WN}(555) due to instrument self-shading as a function of chl *a*.

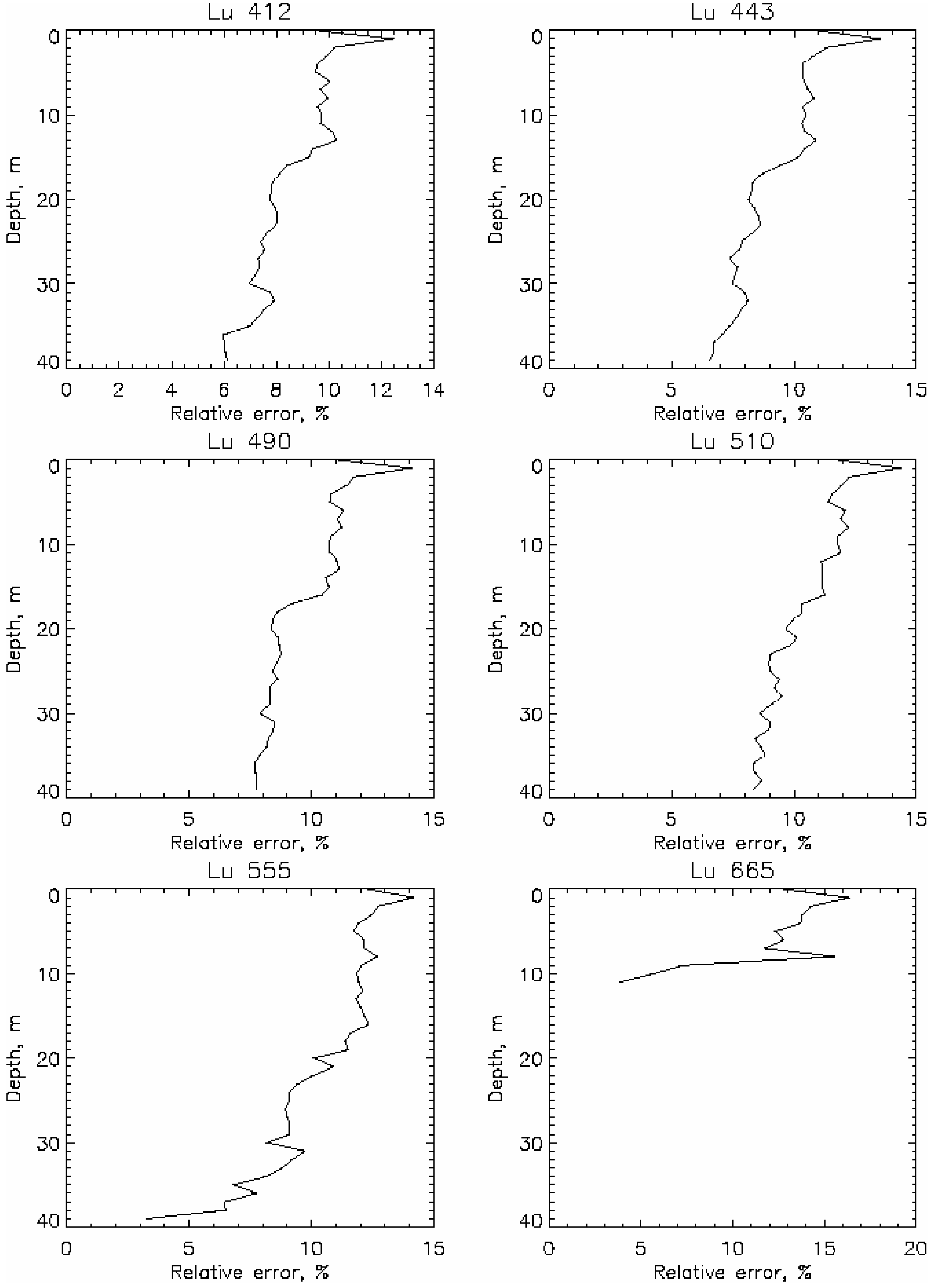

Figure 4. Relative error of the upwelling radiances L_u at SeaWiFS wavelengths estimated from the variability between multiple vertical casts.

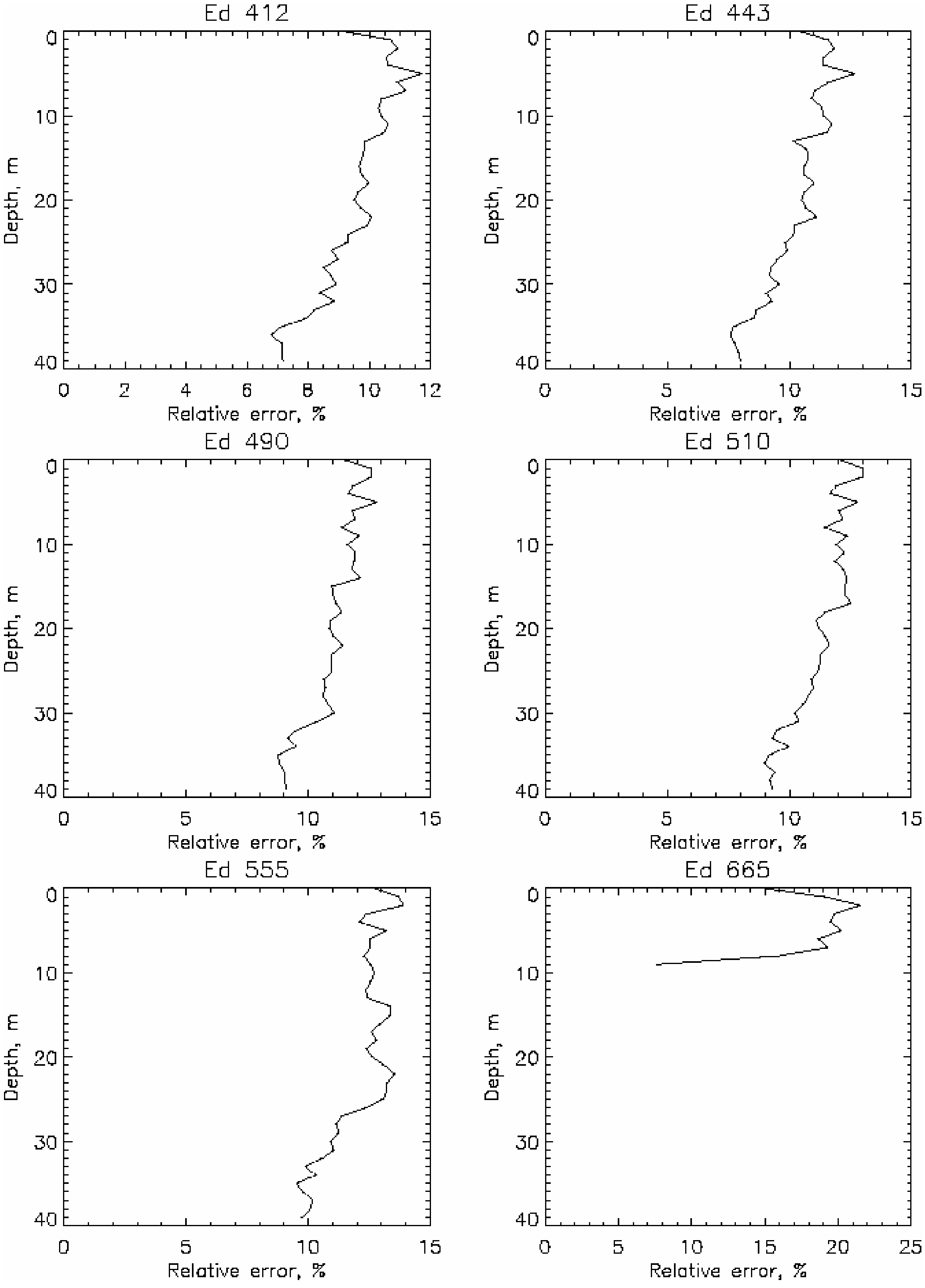

Figure 5. Relative error of the downwelling irradiances E_d at SeaWiFS wavelengths estimated from the variability between multiple vertical casts.

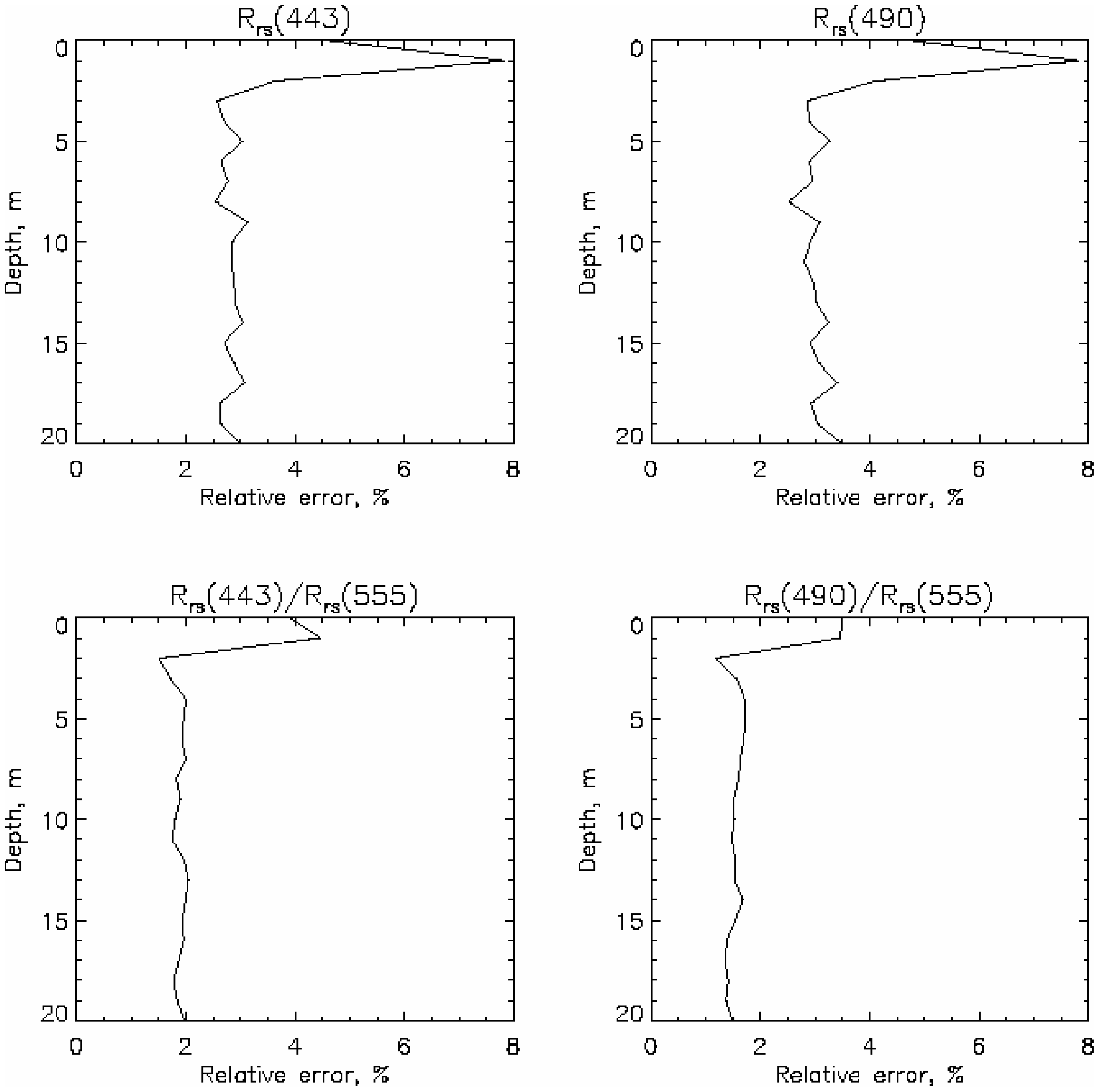

Figure 6. Relative error of the reflectances R_{rs} (443) and R_{rs} (490) and reflectance ratios R_{rs} (443)/R_{rs} (555) and R_{rs} (490)/R_{rs} (555) estimated from the variability between multiple vertical casts.

DISCUSSION AND CONCLUSIONS

Bio-optical measurements required to validate satellite ocean color measurements are difficult to conduct in ways that make the *in situ* versus satellite comparisons meaningful. The drastic differences in spatial scales are just one obvious aspect of the differences between the two measurement platforms. Many individual factors contribute to the error budgets of in-water optical measurements. We have evaluated the influence of the errors due to the self-shading of the in-water instrument as well as due to small-scale spatial and temporal variability.

It appears that the self-shading correction of *Gordon and Ding* [1992] has a significant influence (5% or more) on estimates of L_{WN} at relevant SeaWiFS bands for chl *a* > 1.0 mg m^{-3}. At our highest chl *a* (32.5 mg m^{-3}) the effect is about 30%. The relative error in L_{WN} due to instrument self-shading shows a regular relationship with chl *a* (Figure 2) and could be used to make a simple self-shading correction when the information needed to perform the *Gordon and Ding* [1992] correction is not available, e.g. for the SeaBAM data set. The effects of self-shading are reduced by approximately a half when the typical L_{WN} ratios, $L_{WN}(443)/L_{WN}(555)$ and $L_{WN}(490)/L_{WN}(555)$, are used. The correction of *Gordon and Ding* [1992] itself includes many uncertain and hard to measure variables (effective radius of the instrument taking into account effects of other components of the profiling package; the ratio of the diffuse skylight to direct sunlight; the total absorption coefficient). Therefore, our error estimates can only be regarded as a first approximation.

We also estimated the effects of environmental and methodological small-scale (spatial and temporal) noise. Under near-ideal conditions estimates of L_u and E_d have relative errors approximately 10% (close to 20% at 665 nm). The error is reduced to a half in estimates of L_{WN} and R_{rs} due to normalization by in-water E_d. When typical reflectance ratios $R_{rs}(443)/R_{rs}(555)$ and $R_{rs}(490)/R_{rs}(555)$ are calculated, the relative error is reduced further to about 4%. These measurements were made under near-ideal conditions in the Ross Sea. In the CalCOFI data set these errors are probably significantly higher due to stronger surface effects and problems with avoiding the ship shadow (e.g. orienting the ship in conditions of strong winds and waves).

REFERENCES

Gordon, H.R. and K. Ding, Self-shading of in-water optical instruments, *Limnol. Oceanogr. 37*, 491-500, 1992.

Kahru, M., and B.G. Mitchell, Spectral reflectance and absorption of a massive red tide off southern California, *Journal of Geophysical Research*, 103(C), 21601-21610, 1998.

Kirk, J.T.O., Volume scattering function, average cosines, and the underwater light field, *Limnol. Oceanogr*., 36, 455-467, 1991.

Mitchell, B.G. and M. Kahru, Algorithms for SeaWiFS standard products developed with the CalCOFI bio-optical data set, *Cal. Coop. Ocean. Fish. Invest. R.,* 39:133-147, 1998.

Mueller, J.L. and R.W. Austin, Ocean optics protocols for SeaWiFS validation, Revision 1, NASA Technical Memorandum 104566, Vol. 25, SeaWiFS Technical Report Series, NASA, Greenbelt, MD, 1995.

O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru, and C.R. McClain, Ocean color chlorophyll algorithms for SeaWiFS, *J. Geophys. Res.*, 103(C):24,937-24,953, 1998.

Zibordi, G., and G.M. Ferrari, Instrument self shading in underwater optical measurements: Experimental data, *Appl. Opt., 34,* 2750-2754, 1995.