A test of empirical and semi-analytical algorithms for euphotic zone depth with SeaWiFs data off southeastern China

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ABSTRACT

This study employs SeaWiFS data over the waters off the southeastern China to evaluate a semi-analytical algorithm for euphotic zone depth (Z_e). This algorithm is based on water's inherent optical properties (IOPs), which can be near-analytically calculated from spectral remote-sensing reflectance, where remote-sensing reflectance can be derived from the normalized water-leaving radiance provided by SeaWiFS. In the Taiwan Strait, compared with in situ Z_e (±3 hour within SeaWiFS collection), average error (ε) is 15.0 % and root mean square error (RMSE) is 0.074, with Z_e in a range of 14-34 m from field measurements. In the South China Sea, compared with in situ Z_e (±48 hour within SeaWiFS collection),ε is 5.1 % in summer and 22.6 in winter, while RMSE is 0.032 in summer and 0.129 in winter, with Z_e in a range of 10-82 m from field measurements. For comparison, we also evaluate the performance of the empirical Z_e algorithm that is based on chlorophyll concentration. It is found that the IOP-centered approach has higher accuracy compared to the chlorophyll-a centered approach (e.g. in the South China Sea in winter, ε is 55.3 % and RMSE is 0.219). The new algorithm is thus found not only worked well with waters of the Gulf of Mexico, Monterey Bay and the Arabian Sea, but also worked well with waters of the China Sea.

Key words：China Sea；Euphotic zone depth；Remote sensing quasi-analytical algorithm；SeaWiFS; Chlorophyll

1. INTRODUCTION

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14. ABSTRACT
This study employs SeaWiFS data over the waters off the southeastern China to evaluate a semi-analytical algorithm for euphotic zone depth (Z_e). This algorithm is based on water's inherent optical properties (IOPs), which can be near-analytically calculated from spectral remote-sensing reflectance, where remote-sensing reflectance can be derived from the normalized water-leaving radiance provided by SeaWiFS. In the Taiwan Strait, compared with in situ Z_e (±3 hour within SeaWiFS collection), average error() is 15.0 % and root mean square error (RMSE) is 0.074, with Z_e in a range of 14-34 m from field measurements. In the South China Sea, compared with in situ Z_e (±48 hour within SeaWiFS collection), is 5.1 % in summer and 22.6 in winter, while RMSE is 0.032 in summer and 0.129 in winter, with Z_e in a range of 10-82 m from field measurements. For comparison, we also evaluate the performance of the empirical Z_e algorithm that is based on chlorophyll concentration. It is found that the IOP-centered approach has higher accuracy compared to the chlorophyll-a centered approach (e.g. in the South China Sea in winter, is 55.3 % and RMSE is 0.219). The new algorithm is thus found not only worked well with waters of the Gulf of Mexico, Monterey Bay and the Arabian Sea, but also worked well with waters of the China Sea.

15. SUBJECT TERMS
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The euphotic zone is a layer where light is sufficient for phytoplankton production by photosynthesis to exceed the loss of material that takes place through respiration [1]. Although the disphotic zone has attracted increasing attention recently [2], the euphotic zone is nevertheless the most important in the context of ecosystem dynamics [3,4] and air-sea interaction through transfer of either heat [5] or materials, in particular green house gases such as CO_2 [6,7]. In practice, the euphotic zone depth (Z_e) is defined as the depth at which PAR (photosynthetic available radiation) value is 1% of the surface value [8]. Similar as Secchi disk depth, Z_e is a measure of water clarity and is much more robust. Because Z_e is a cumulative measure of biogeochemical properties of the upper-water column, changes of Z_e also depict environmental patterns that might be tightly associated with the climate.

There are various approaches to estimate Z_e from ocean color remote sensing. One simple empirical method is based on Case-1 water assumptions [9,10], where Z_e is calculated from remotely derived concentration of chlorophyll-a ([Chl]) [9]. Recently, Lee et al. [11] developed an analytical model to describe the vertical attenuation of downwelling vector irradiance in the visible domain. Based on this model, Z_e can be easily calculated when IOPs (the absorption and backscattering coefficients at 490 nm, in particular) are known, either from in situ measurements or from remote sensing of ocean color [12]. This IOP-centered approach was evaluated with ship-borne measurements made over three different regions (the Arabian Sea, the Monterey Bay and the Gulf of Mexico) at different seasons. It was found that the Z_e values calculated via Rrs-derived IOPs were within ~14% of the measured values on average, while the error was ~33% when Z_e was calculated via Rrs-derived [Chl]. However, how this approach performs in other regions keeps unknown. In this study, we test the performances of the IOP-centered approach [12] and the [Chl] approach [9] for waters off the southeastern China. More importantly, to the best of our knowledge, it is the first time that both approaches are tested with match-up data assembled from *in situ* measurements and from the SeaWiFS ocean color. The calculated Z_e are compared with those from profiles of PAR measurements to evaluate the performance of the approaches.

2. BACKGROUND OF THE REGION UNDER STUDY

The region we do the tests for the Z_e performance includes the Taiwan Strait and the South China Sea (Fig.1). The Taiwan Strait (TWS), with an average water depth of 60 m, is a shallow shelf-channel that connects the South China Sea (SCS) with the East China Sea (ECS). Warm, saline, and oligotrophic water enters the TWS from the SCS while cold, fresh, and eutrophic water intrudes into the TWS from the ECS along the Chinese coast. Their relative influence, which varies seasonally in response to changes in the monsoonal wind, is a major determining factor of the hydrographic conditions and biological productivity in the TWS. Coastal upwelling occurs regularly in summer in this region [13], affecting primary production and fisheries. The near-shore waters receive inputs of coastal runoff, including Minjiang, Jinjiang, Jiulong Jiang and Hanjiang rivers with high loads of nutrients and other terrestrial substances.

The South China Sea (SCS) is one of the major marginal seas. The Pearl River discharges into its northeast, through which the SCS receives freshwater as well as nutrients and pollutants from one of the most industrialized regions of China. Climatic variations in the atmosphere and the upper ocean of the SCS are primarily controlled by the East Asian monsoon, which follows closely the variations in the equatorial Pacific [14]. Recent arguments emerged towards a role of CO_2 source the SCS played [15, 16].

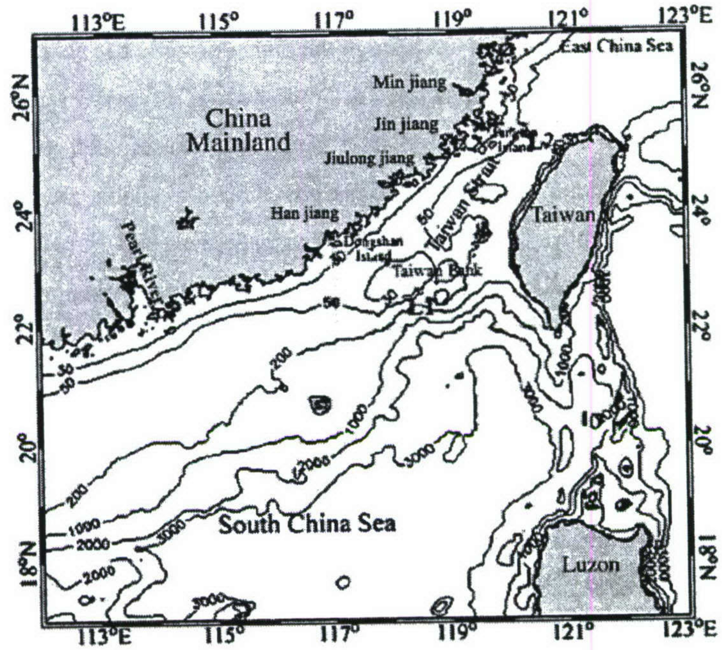

Figure1. The map of the region for test of Z_e algorithm performance

3. DATA AND METHODS

3.1 Z_e from *in situ* PAR

Field measurements of PAR were carried out in August 1998 and 1999 and July-August 2004 for the TWS, and in February 2004 and July and December 2006 for the SCS. Figure 2 shows the sampling stations. Instantaneous PAR (400–700 nm) in the upper water column at time t (PARt(z)) and depth z was measured by a PAR sensor (Biospherical Instruments, Inc.) mounted on a SeaBird CTD rosette. During these measurements the above-surface solar zenith angles (θ_a) were between 8° and 77° (55 measurements in total, of which 16 (27%) had $\theta_a > 50°$).

Following Lee et al. [12], Z_e was determined by calculating the ratio of PAR at depth z to surface PAR (PAR(0)) as below:

$$r_{PAR}(z) = \frac{PAR(z)}{PAR(0)} \tag{1}$$

Z_e is the depth z where $r_{PAR}(z) = 0.01$.. Because depth was rarely recorded with $r_{PAR}(z)$ exactly 1%, an approximation was obtained by exponentially interpolating $r_{PAR}(z)$ between 0.9% and 1.1%. For some measurements in the SCS, the PAR sensor did not provide a reading when PAR(z) was 1% of PAR(0). In that case, only the depth z of 10% of PAR(0) was directly obtained from PAR profiles. For the other stations where both depths 10% and 1% of PAR(0) (Z_e & $Z_{10\%}$) were obtained from PAR(z), it was found that a good polynomial relationship existed between Z_e and $Z_{10\%}$ (Fig.3). The following function was derived:

$$Z_e = -0.0194*Z_{10\%}^2 + 2.7619*Z_{10\%} - 3.6721 \; (4.6 < Z_{10\%} < 56.9 \text{ m}) \tag{2}$$

This relationship is slightly different from that of Lee et al.[12], which could be due to that our data here covers a much wider range of $Z_{10\%}$ (4.6 – 57 m instead of 2.1 – 29 m). Therefore, for those stations where no Z_e was obtainable from $PAR(z)$, Z_e values were estimated by applying equation (2).

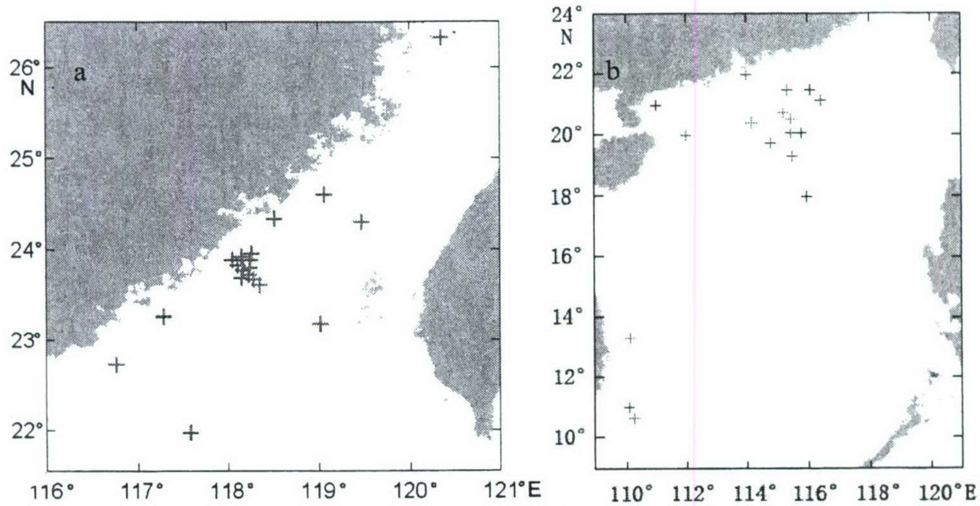

Figure 2. Location of stations for PAR measurements in the Taiwan Strait (a) and the South China Sea (b). In Fig.2b, the red and the blue crosses marked the stations sampled in February and July 2004, respectively.

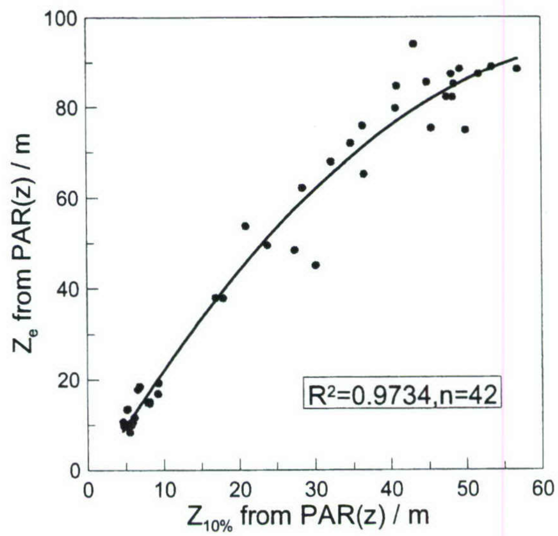

Figure 3. Relationship between Z_e and $Z_{10\%}$ from in situ PAR profiles in the South China Sea

3.2 Remotely sensed Z_e

For the dates having field PAR data, remote sensing reflectance (R_{rs}) were calculated from SeaWiFS daily Level-2 data which were obtained from the NASA Distributed Active Archive Center (DAAC). The resolution was 1 km for the TWS and 4 km for the SCS. They were used in the OC4v4 band ratio algorithm [17] to calculate [Chl], and then Z_e was derived from:

$$Z_e = a([\mathrm{Chl}])^b, \tag{3}$$

where the a value was 34.0 and the b value was -0.39 [9].

In the meanwhile, the absorption and backscattering coefficients at 490 nm, $a(490)$ and $b_b(490)$, were derived from R_{rs} by applying the updated QAA [12, 18]. $K_{VIS}(z)$, the attenuation coefficient of E_{VIS} (downwelling irradiance in the visible domain, 350–700 nm), was then calculated as a function of $a(490)$, $b_b(490)$ and the sun angle (θ_a) [11]. The IOP-centered Z_e [12] was thus derived based on the following equation:

$$K_{VIS}(Z_e) \cdot Z_e = 4.605 \tag{4}$$

3.3 Comparison of field data with remote sensed data

Due to frequent cloud cover in the study region, matching data pairs with *in situ* data collected within ±2–3h of the satellite overpass for a rigorous comparison [19] were limited, especially in the SCS. Matching pairs having the time differences of ±3 h at the corresponding cruise survey locations were collected for the TWS. However, for the SCS a window of ±48 h was chosen in order to obtain enough matching pairs to ensure statistically meaningful results.

For simplification, hereafter the Z_e values derived from field PAR data were annotated as Z_e^M, those from the [Chl]-centered approach as Z_e^C and from the IOP-centered approach as Z_e^I.

Following Lee et al.[12], we used the root mean square in log scale (RMSE) and an averaged percentage error (ε) as measures to describe the similarity/difference between the *in situ* and satellite data sets.

$$\varepsilon = \left(\frac{1}{n} \sum_{i=1}^{n} \left| \frac{(Z_e^I)_i - (Z_e^M)_i}{(Z_e^M)_i} \right| \right) \times 100\% \tag{5}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\log((Z_e^I)_i) - \log((Z_e^M)_i]) \right)^2} \tag{6}$$

RMSE and ε were calculated for Z_e^C by substituting Z_e^I with Z_e^C in Equation 5 & 6.

4. RESULTS AND DISCUSSION

Figures 4-6 showed Z_e^M versus Z_e^C and Z_e^I, respectively. Table 1 summarized the error estimates, both in our study region and in the Monterey Bay, the Gulf of Mexico and the Arabian Sea (abbreviated as MAG) [12].

All the three cruises in the TWS were carried out in summer. The averaged percentage error (ε) between Z_e^M and Z_e^I was 15.0% (with a maximum error of 53.6%) for a range of ~16–34 m from PAR measurements. By contrast, ε between Z_e^M and Z_e^C was 40.1% while the maximum error was 99.1%. The root-mean-square error in log scale (RMSE) for Z_e^I was 0.074, significantly smaller than the RMSE (0.159) of Z_e^C.

For the summer case of the SCS (July 2004), the performance of Z_e^I and Z_e^C was close to each other. ε was 5.1% for Z_e^I (maximum error 17.1%) while it was 7.2% for Z_e^C (maximum error 21.3%). RMSE was 0.032 for the former and 0.041 for the latter. Nevertheless, the winter case of the SCS (Feb.2004) was different. ε for Z_e^C (55.3%) was more than double of that for Z_e^I (22.6%). RMSE was 0.219 for Z_e^C whereas it was 0.129 for Z_e^I.

It was obvious that the performance of the IOP-centered approach was better than that of the [Chl]-centered approach for data in this study. The average error and RMSE were comparable to those published in the Ref.12. Our region, the southern part of the China Sea, covered a wide range of waters, from very shallow near shore water (~ 30 m depth) to the deep basin (~2000 m depth). The range of surface [Chl] was ~0.01–6.29 mg/m^3 with Z_e ranging from ~16 to 80 m. This result was particularly encouraging because we used SeaWiFS *Rrs* data to evaluate algorithms that were developed independently.

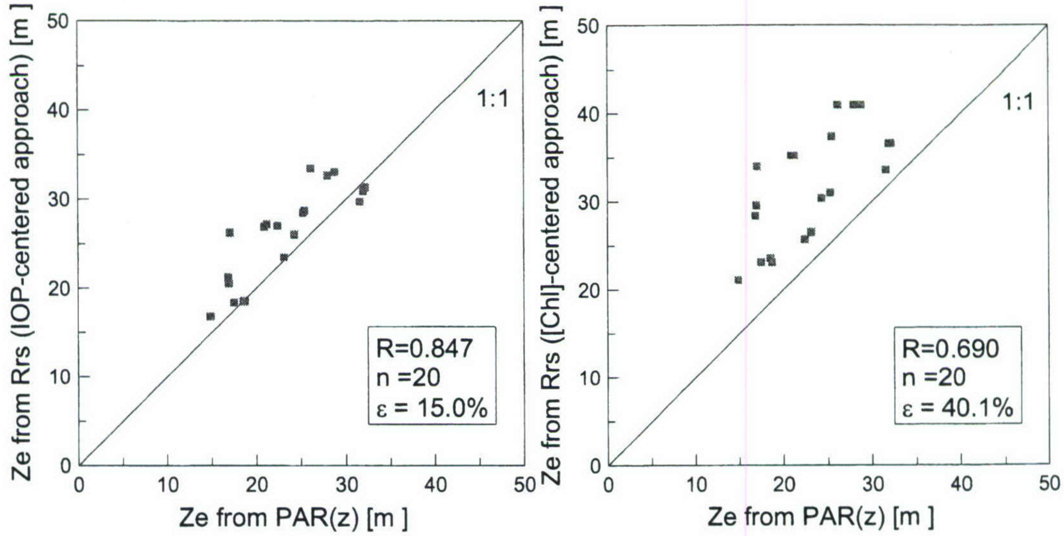

Figure 4. Comparison between satellite Z_e and the Z_e derived from *in situ* PAR profile in the Taiwan Strait (a) from IOP-centered approach, (b) from [Chl]-centered approach.

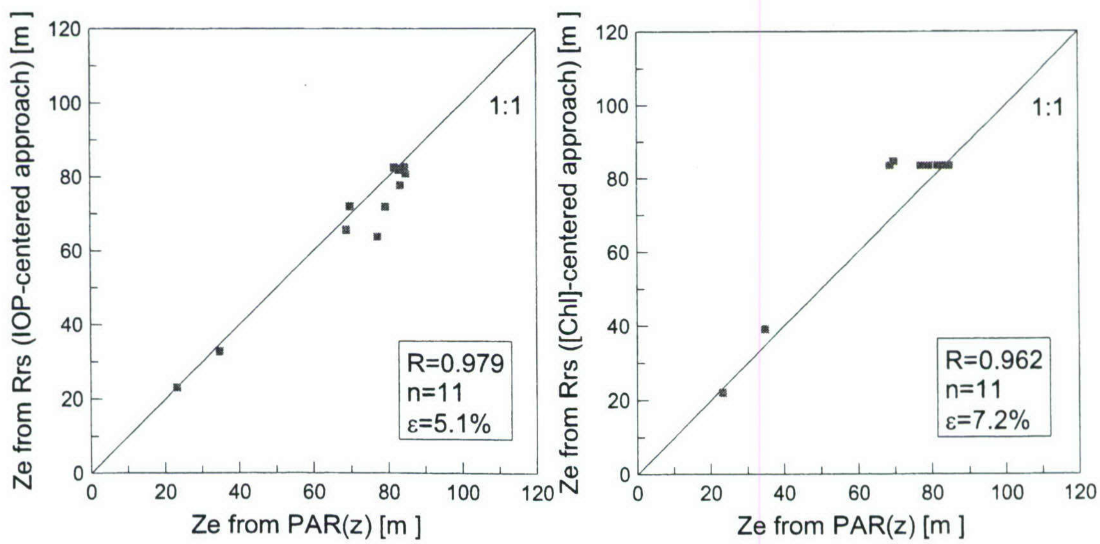

Figure 5. Comparison between satellite Z_e and the Z_e derived from in situ PAR profile in the South China Sea in July 2004 (a) from

IOP-centered approach, (b) from [Chl]-centered approach.

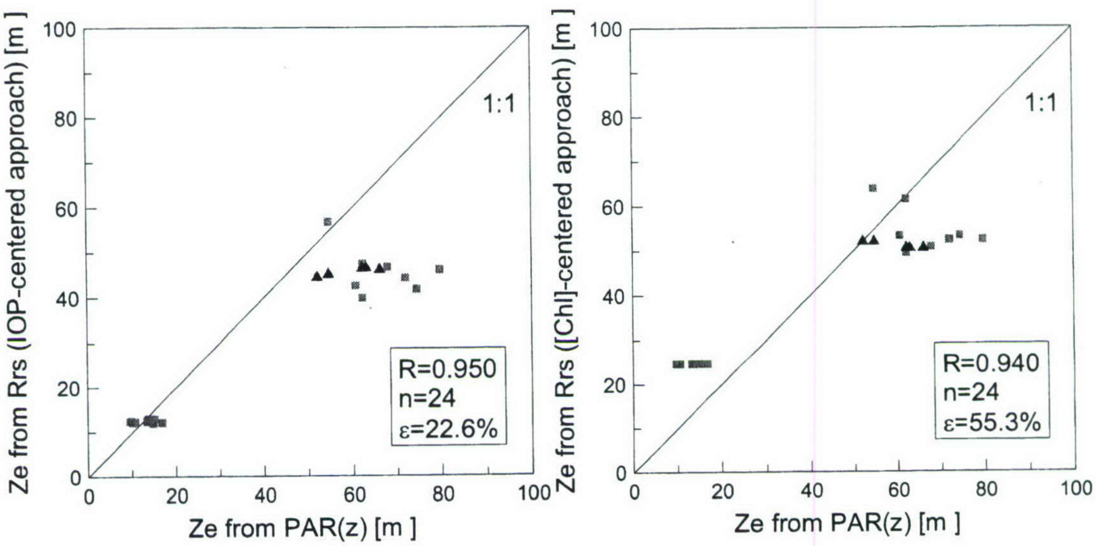

Figure 6. Comparison between satellite Z_e and the Z_e derived from in situ PAR profile in the South China Sea in February 2004 (a) from IOP-centered approach, (b) from [Chl]-centered approach.

Table 1 Error characters for the comparison between the Z_e derived from *in situ* PAR profiles and from SeaWiFS *Rrs*

	IOP-Centered Approach			Chl-Centered Approach			n	References
	Average error(%)	Max.error (%)	RMSE	Average error(%)	Max.error (%)	RMSE		
TWS (summer)	15.0	53.6	0.074	40.1	99.1	0.159	20	This study
SCS (summer)	5.1	17.1	0.032	7.2	21.3	0.041	11	This study
SCS (winter)	22.6	43.9	0.129	55.3	153.4	0.219	24	This study
SCS (autumn)	6.6*	N/A	N/A	10.7	N/A	N/A	5	21
MAG	13.7	63.5	0.079	32.7	218	0.162	64	12

* An empirical algorithm based on Kd(490) [21] rather than the IOP-centered approach [12] was applied.

The performance of the IOP-centered approach in the TWS looked not as good as that in the SCS in summer, and it also appeared worse in winter than in summer in the SCS. One potential reason for the excellent performance in the SCS in summer was that all of the 11 data points (there were 8 measurements at one station to obtain a time-series observation) obtained in clear oligotrophic water, where IOPs derived from Rrs could be more accurate and the waters could be more uniform. Even for the station relatively near shore (see Fig.2b for the location), [Chl] was about 0.2 mg/m^3 at 75 m (generally the depth of the subsurface [Chl] maximum) [20]. On the contrary, all the TWS data were collected in shallow and relatively optically complex waters, where there could be more spatial variation and it is harder to achieve accurate atmospheric correction. In addition, for 62% of the *in situ* measurements in the SCS in winter the sun angles were >50° while 29% of them were >70°. The IOP-centered approach, however, was developed with sun angles as high as 60°. The results here suggest that fine adjustment to the IOP-centered approach might be necessary. Nevertheless, the overall excellent agreement between SeaWiFS Z_e and *in situ* Z_e provide initial but significant indication that euphotic zone depth of wide areas can be well derived from satellite data (such as SeaWiFS *Rrs*) with the IOP-centered approach, although more evaluations with *in situ* observations are certainly necessary and helpful.

Tang et al. [21] recently developed an empirical algorithm for Z_e based on $K_d(490)$ of the SCS, which calculated Z_e from MODIS ocean color data ($K_d(490)$). They compared the calculated Z_e with the result from [Chl]-centered approach and the *in situ* Z_e from SPMR for measurements made in September 2004. Due to measurement limitations, the data covered in that study had only five points with Z_e in a range of 30-70 m, which may not be enough to show statistical significance.

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