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Bridging between SeaWiFS and MODIS for continuity of chlorophyll-*a* concentration assessments off Southeastern China

Caiyun Zhang [a,b], Chuanmin Hu [c], Shaoling Shang [a], Frank E. Müller-Karger [c], Yan Li [a], Minhan Dai [a], Bangqin Huang [a], Xiuren Ning [d], Huasheng Hong [a,*]

[a] *State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, Fujian 361005, China*
[b] *Department of Oceanography, College of Oceanography and Environmental Sciences, Xiamen University, Xiamen, Fujian 361005, China*
[c] *College of Marine Science, University of South Florida, 140 7th Avenue South, St. Petersburg, FL 33701, USA*
[d] *Key Lab of Marine Ecosystems and Biogeochemistry of State Oceanic Administration, Hangzhou, Zhejiang 310012, China*

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Abstract

Chlorophyll-*a* (Chl) concentration in the Taiwan Strait (TWS) and in the South China Sea (SCS) was estimated using time series of satellite data collected with the MODIS/Aqua and SeaWiFS instruments, and validated with in situ measurements from three cruises conducted in winter and summer 2004. For Chl between 0.1 and 10 mg m^{-3}, both SeaWiFS and MODIS agreed well with in situ data. Errors for turbid coastal waters were larger than for offshore waters but the overall RMS (root mean square) error in log scale was within 0.35. The percentage RMS error was much larger, varying between 60% and 170% for open ocean and most of the shallow (<30 m), coastal regions. However, there was no large systematic error or significant bias in either satellite data set, and these numbers were comparable to those for other global oceans and not significantly larger than the algorithm "noise" (0.22 in RMS error in log scale). Further, SeaWiFS and MODIS showed similar spatial and temporal patterns between July 2002 and October 2004, as well as nearly identical concentrations for Chl between 0.1 and 4 mg m^{-3}. RMS difference between the two data sets of monthly mean Chl for several sub-regions was generally <11% and <0.05 (after logarithmic transformation). For each individual month, the statistics (mean, mode, median) of the two data sets for the entire study region (6–9 × 10^5 satellite pixels at ~1 km resolution) were very similar, with RMS differences typically between 30% and 40% and between 0.10 and 0.15 (after logarithmic transformation), where no significant bias was found. Therefore, it would be possible to continue the time series using only one sensor such as MODIS, in the eventual absence of SeaWiFS. Further research is needed to improve the remote sensing algorithms for application in turbid coastal waters.
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Keywords: Remote sensing; Ocean color; Continuity; Chlorophyll a; SeaWiFS; MODIS; Taiwan Strait; South China Sea

1. Introduction

Assessment of environmental change over long periods of time requires a time-series of consistent observations. Phytoplankton pigment concentrations such as chlorophyll-*a* (Chl) provide a measure of the biological state of the surface ocean. Satellite sensors designed to observe the Visible Sea Spectral Reflectance (VSSR, traditionally called ocean color) provide estimates of short-term (seasonal and inter-annual) to long-term (decadal) changes in the global ocean Chl (e.g., Behrenfeld et al., 2001; Gregg & Conkright, 2002; Gregg et al., 2003). However, for a particular region, especially a coastal region, the accuracy of the long-term trend is often unknown due to uncertainties associated with satellite data products.

Of particular interest are observations from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) that has operated since 1997 (McClain et al., 1998) and from the two Moderate Resolution Imaging Spectroradiometers (MODIS), including Terra MODIS (since 1999) and Aqua MODIS (since 2002) (Esaias et al., 1998). These satellite sensors provide near-daily coverage of the global ocean. Continuity in coverage is

* Corresponding author. Tel.: +86 592 2182216; fax: +86 592 2095242.
E-mail addresses: hhuasheng@gmail.com, hshong@xmu.edu.cn (H. Hong).

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expected with the future National Polar-Orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Mission (NPP; expected launch in 2008), which will carry the Visible/Infrared Imager/Radiometer Suite (VIIRS) instruments, which are similar in capability to SeaWiFS and MODIS.

Some efforts have been made to merge global time series from different VSSR (i.e., ocean color) sensors, primarily the Coastal Zone Color Scanner and SeaWiFS (Gregg & Conkright, 2001; Siegel & Maritorena, 2000; Yoder et al., 2001). But little has been done on merging global-scale SeaWiFS and MODIS series. SeaWiFS is a well-calibrated and stable sensor (McClain et al., 2004). In comparison, there is a general perception that MODIS data are of lower quality due to the publicity that several artifacts in sensor design have received (for example stray light, polarization, and data striping). The future availability of SeaWiFS data is not clear, since the mission has exceeded its 5-year life design. However, MODIS is expected to continue into the future and provide a bridge to VIIRS. To enable a smooth transition from SeaWiFS to MODIS, it is necessary to assess differences between these sensors. Such comparison is particularly useful to regional investigators, given that some limited regional comparisons have shown large variations (Blondeau-Patissier et al., 2004; Darecki & Stramski, 2004). Here we present the first validation and comparison results for observations of Chl in the Taiwan Strait (TWS) and the northern South China Sea (SCS) to assess the utility of MODIS in case that SeaWiFS data may not be available in the future.

The TWS and the northern SCS are located along the southeast coast of China (Fig. 1). The region is characterized by marked seasonal changes in physical (Jan et al., 2002; Su, 2004) and biological properties (Liu et al., 2002; Ning et al., 2004). The near-shore, shallow (<200 m) waters of the northern SCS receive significant inputs of coastal runoff with high loads of nutrients and other terrestrial substances, including contributions from the Pearl River. Further, coastal upwelling occurs regularly in this region (Hong et al., 1991), affecting primary production and fisheries. Over half of the area of the TWS is <50 m deep. These shallow regions are optically complex compared to the adjacent deep SCS.

Preliminary studies used SeaWiFS data to examine the variability of surface chlorophyll-*a* (Chl) and driving factors in the SCS and TWS regions (e.g., Lin et al., 2003; Shang et al., 2004a; Tang et al., 2002). However, validation of the SeaWiFS products has been sparse because extensive and reliable in situ measurements have not been available. Further, no comparison has been made between SeaWiFS and MODIS for this region.

This study addresses two major questions:

1) How accurate are Chl estimates derived from SeaWiFS and MODIS?
2) How do MODIS data products compare with those from SeaWiFS?

Answering these questions will help develop a consistent, long-term Chl time-series off southeastern China, which is the

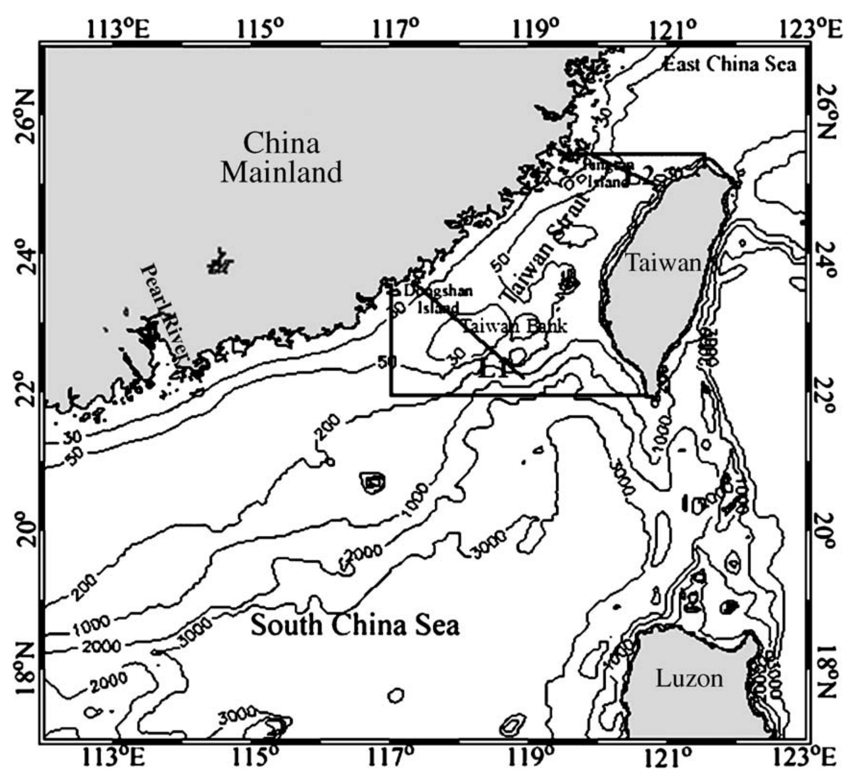

Fig. 1. Map showing the study area, with the Taiwan Strait as used here defined by solid lines. Overlaid on the map are the bathymetry contours (unit: meter) and two cross-shelf transect lines where chlorophyll from MODIS and SeaWiFS were extracted and analyzed.

first step leading to a better understanding on temporal patterns of Chl in response to physical fluctuations and their relationship with local and remote forcing.

2. Data and methods

2.1. Cruise survey

In situ data were collected from three cruises (Fig. 1) in 2004. Two cruises were conducted in the northern SCS from 9 February to 6 March 2004 (identified below as February 2004) and from 6 to 23 July 2004 (identified below as July 2004). A third cruise was conducted in the southern TWS from 26 July to 7 August 2004 (identified below as August 2004). Water samples were collected with 1.7L Niskin bottles mounted on a rosette equipped with a SBE19 CTD. Sampling locations are shown in Fig. 2. Samples were filtered with Whatman GF/F glass fiber filters, and chlorophyll-*a* concentration (Chl) was determined by extracting pigments in acetone and measuring fluorescence emission on a fluorometer (Parsons et al., 1984). During the summer cruises, surface temperature, salinity, and chlorophyll fluorescence were measured along the ship track using a SeaBird SBE21 thermosalinograph and a WETLabs WETStar fluorometer. The mean and standard deviation for the Chl data from the discrete water samples in July 2004 were 0.49 and 1.05, and in August 2004 cruises were 0.59 and 0.46. They were used to calibrate/convert the flow-through fluorescence as follows: Chl = 7.840(±0.296)*fluorescence − 0.561(±0.055), $0.05 < \text{Chl} < 5.14$, $r = 0.98$, $n = 34$ for July 2004 cruise; and Chl = 4.029 (±1.009)*fluorescence − 0.157(±0.204), $0.08 < \text{Chl} < 1.73$, $r = 0.73$, $n = 16$ for August 2004 cruise.

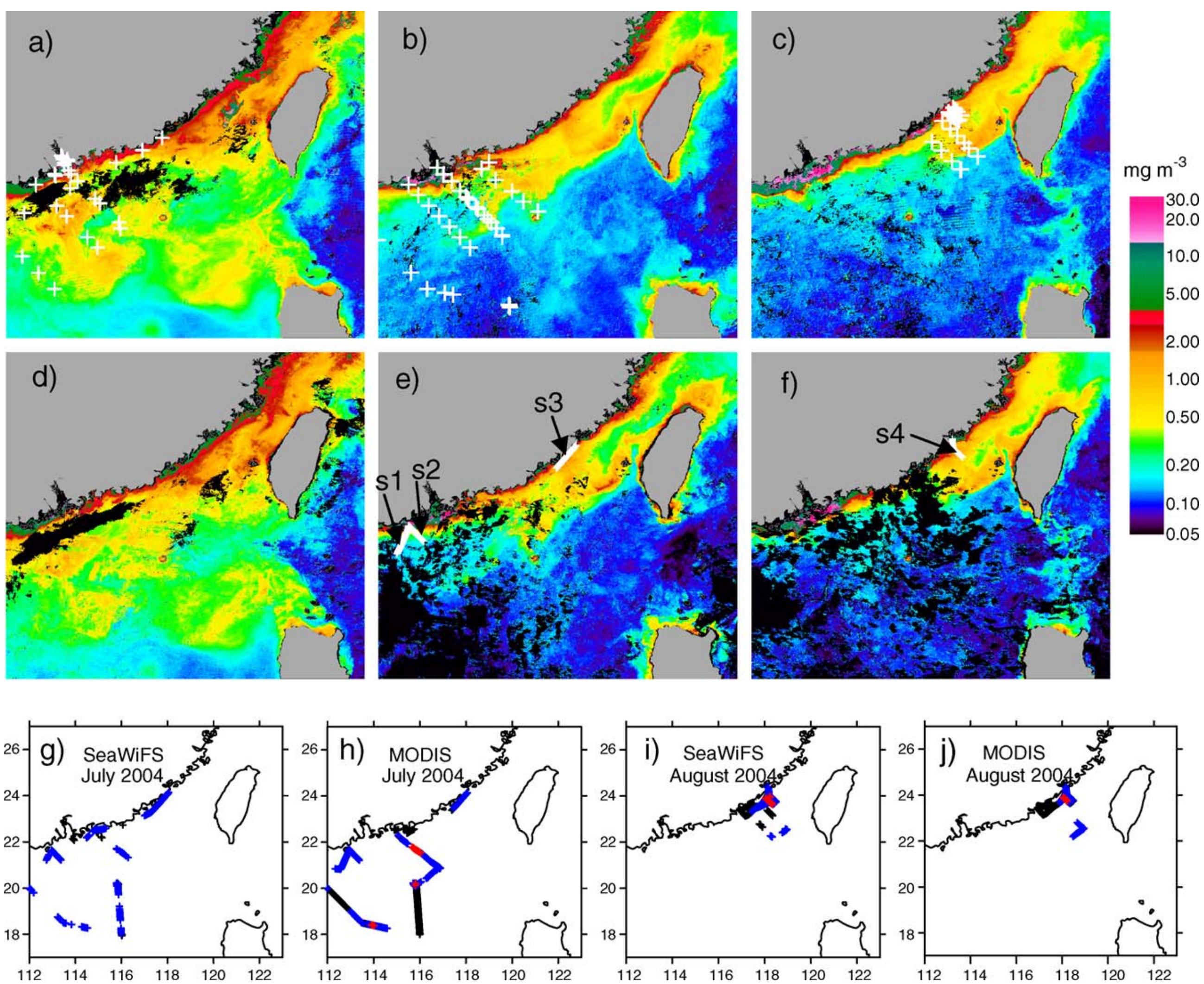

Fig. 2. Composite Chl images from the MODIS (upper panels) and SeaWiFS (middle panels) sensors for the three cruise periods in 2004: 9 February–6 March, 6–23 July, and 26 July–7 August. White crosses (+) on the MODIS images mark in situ sampling locations. The white line shown on the SeaWiFS images (S1–S4) show ship transect lines from which SeaWiFS and MODIS data were available for comparison within 24 h of each other. The bottom panels show locations where SeaWiFS and MODIS data were available within ±2 h (red), ±24 h (blue), and ±48 h (black) of in situ flow-through Chl observations during the July 2004 and August 2004 cruise periods.

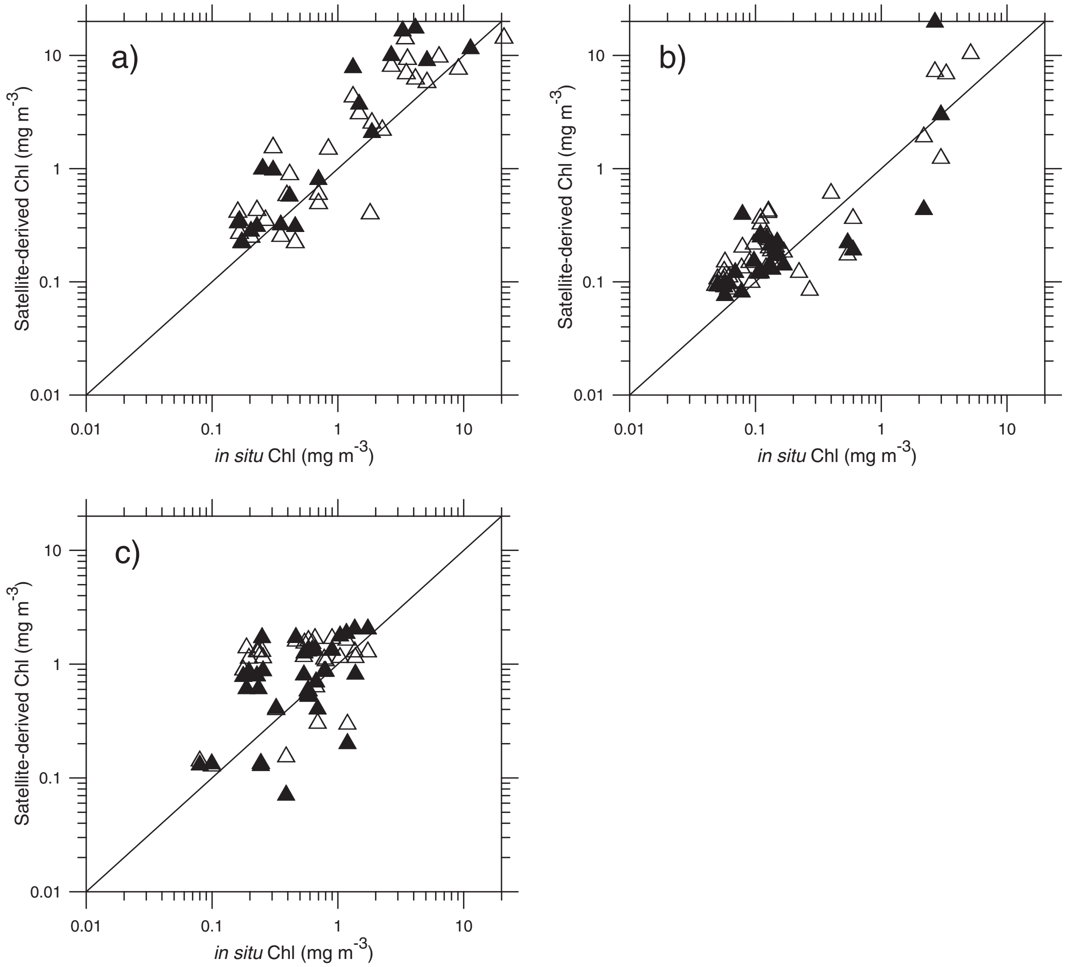

Fig. 3. Comparison of Chl obtained from in situ sampling, SeaWiFS (▲), and MODIS (△) for the three cruise periods in February 2004 (a), July 2004 (b), and August 2004 (c). The satellite data were extracted from the composite images and therefore may not be strictly concurrent with the in situ measurements.

2.2. Satellite (SeaWiFS and MODIS) data

SeaWiFS daily Level-1A data between September 1997 and October 2004 were obtained from the NASA Distributed Active Archive Center (DAAC). They were processed to Level 2 Chl data products using the SeaWiFS Data Analysis System (SeaDAS4.6) software, and then mapped to a cylindrical equidistant projection at ~1 km/pixel resolution. Atmospheric effects were removed with the Gordon and Wang (1994) algorithm to obtain the normalized spectral water-leaving radiance ($nL_w(\lambda)$), which were then used in the OC4v4 band-ratio algorithm (O'Reilly et al., 2000) to estimate Chl. The daily data were used to generate monthly composite (arithmetic mean) images while discarding suspicious pixels associated with various flags (e.g., cloud/stray light, large solar/sensor angle, high aerosol optical thickness).

Daily MODIS/Aqua data covering the study region (July 2002 to October 2004) were processed by the NASA Goddard Space Flight Center (GSFC) using similar atmospheric correction algorithms as for SeaWiFS (Collection 4) but with the OC3 (O'Reilly et al., 2000) bio-optical algorithm. These data were mapped and averaged in a manner similar to that used for SeaWiFS.

2.3. Comparison between in situ and satellite data

A rigorous comparison requires that in situ data be collected within ±2–3 h of the satellite overpass (Bailey et al., 2000).

Table 1
Comparison between satellite and in situ Chl (discrete samples, Fig. 3)

Cruises	SeaWiFS (swf) vs. in situ Chl (chl)								MODIS (mod) vs. in situ Chl (chl)							
	Slope	Intercept	*R*	*n*	RMS (%)	Bias (%)	log_RMS	log_bias	Slope	Intercept	*R*	*n*	RMS (%)	Bias (%)	log_RMS	log_bias
February 2004	1.10	0.30	0.92	19	203	136	0.395	0.290	0.92	0.19	0.88	29	151	91	0.350	0.192
July 2004	0.81	−0.03	0.81	26	159	69	0.335	0.119	0.85	0.08	0.85	42	112	78	0.313	0.192
August 2004	0.57	0.02	0.50	32	171	94	0.392	0.164	0.43	0.06	0.40	32	249	146	0.444	0.243

Note that the satellite data are from the composite data set covering the entire cruise period, therefore are not strictly concurrent with the in situ measurements.

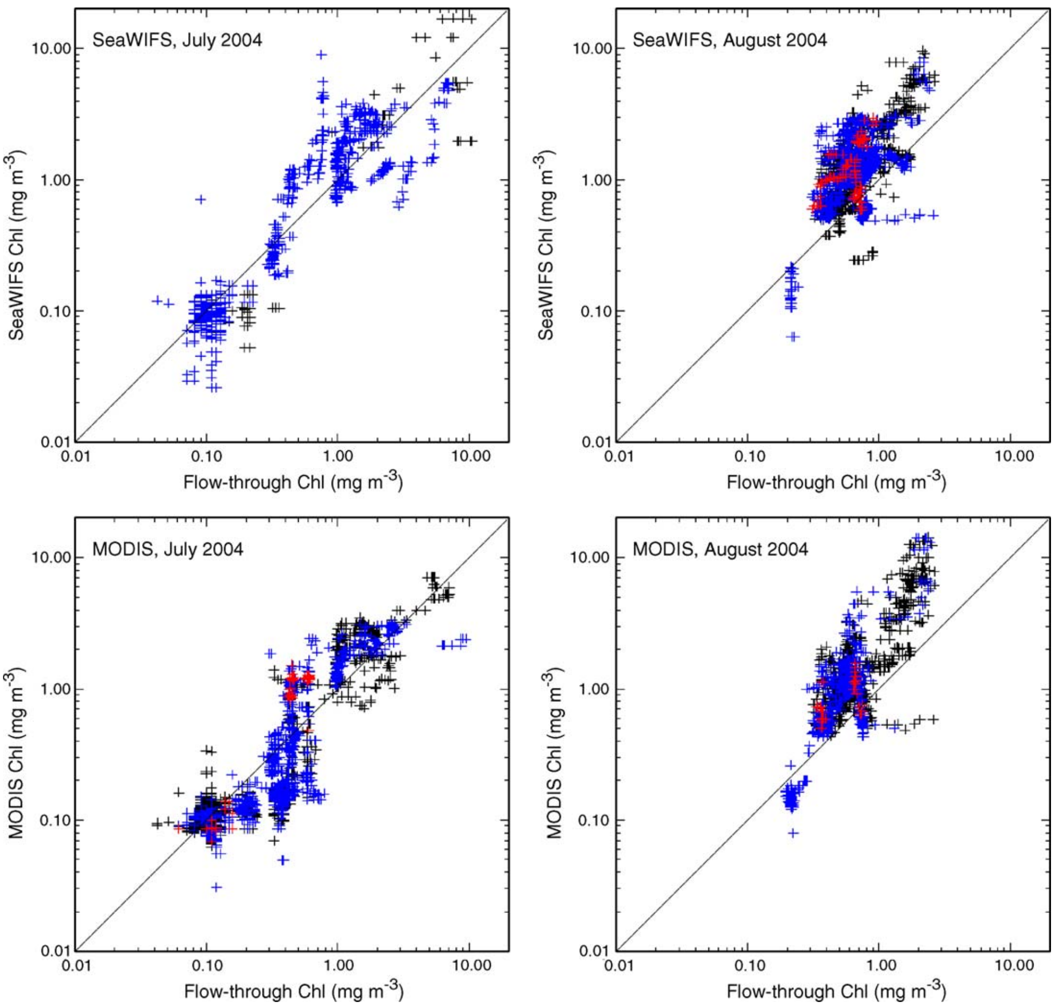

Fig. 4. Comparison of in situ flow-through, SeaWiFS, and MODIS Chl during the July 2004 and August 2004 cruise periods. Colors indicate the time difference between in situ measurements and satellite overpass: ±2 h (red), ±24 h (blue), and ±48 h (black). Solid lines are 1:1 lines.

However, due to frequent cloud cover in the study region, the matching data pairs are often limited. Thus, two methods were used in the comparison.

The first method compared in situ Chl data from discrete water samples with those derived from the composite satellite images at the corresponding cruise survey locations. The second method compared calibrated flow-through data with satellite estimates, where the matching pairs had the time differences of: (A) ±2 h; (B) ±24 h; and (C) ±48 h.

To minimize errors associated with the satellite sensor/algorithm noise, a 3 × 3 median filter was used according to Hu et al. (2001). Similarly, a median value from the multiple in situ flow-through data points collected within an image pixel (~ 1 × 1 km^2) was used.

Table 2
Comparison between satellite and in situ Chl (calibrated flow-through data, Fig. 4)

Cruises		July 2004								August 2004							
	Time difference	Slope	Intercept	R	n	RMS (%)	Bias (%)	log_RMS	log_bias	Slope	Intercept	R	n	RMS (%)	Bias (%)	log_RMS	log_bias
SeaWiFS	2 h	–[a]	–	–	3	–	–	–	–	0.66	0.21	0.44	97	134	111	0.341	0.292
	24 h	1.05	0.05	0.92	827	106	28	0.249	0.0272	0.94	0.23	0.63	917	142	100	0.333	0.245
	48 h	1.04	0.03	0.91	894	104	25	0.259	0.0121	1.04	0.26	0.70	1472	141	100	0.333	0.249
MODIS	2 h	1.58	0.49	0.96	81	105	79	0.295	0.2130	0.61	0.10	0.59	42	86	72	0.251	0.218
	24 h	1.08	−0.05	0.83	1265	66	−1.2	0.279	−0.0876	1.58	0.38	0.84	603	175	95	0.330	0.212
	48 h	1.01	−0.06	0.87	2470	61	−1.8	0.256	−0.0619	1.38	0.34	0.84	1296	171	110	0.349	0.259

The time difference is between satellite and in situ measurements.
[a] "–": too few matching pairs to derive meaningful statistics.

Table 3
Time difference (local time) between in situ, SeaWiFS, and MODIS measurements for transects S1, S2, S3, and S4 (Fig. 2e and f)

Section	Time range of flow-through data	MODIS	SeaWiFS
S1	July 19 1:22–July 19 7:35	July 18 13:55	July 18 13:02
S2	July 19 7:35–July 19 11:53	July 18 13:55	July 18 13:02
S3	July 22 23:15–July 23 04:15	July 22 13:30	July 22 12:27
S4	August 6 19:33–August 7 02:19	August 7 13:30	August 6 12:46

In comparing satellite and in situ data, several different methods have been used in the literature to estimate the errors. Two methods were used in this study to put our results in the context of the published literature. First, following Darecki and Stramski (2004), we used the root mean square (RMS) and mean difference (bias) as measures to describe the similarity/difference between the two different data sets. These errors (in percentage) are defined as follows:

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i)^2} \times 100$$

$$\mathrm{bias} = \bar{x} = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right) \times 100$$

$$x = \frac{S-I}{I} \qquad (1)$$

where S stands for satellite data, I for in situ data, and n is the number of matching pairs. For a normally distributed data set (i.e., x) RMS should equal to standard deviation. Further, because the natural distribution of Chl is lognormal (Campbell, 1995), error estimates were also made on the logarithmically transformed (base 10) data:

$$\mathrm{log\_RMS} = \sqrt{\frac{\sum[(\log(S) - \log(I)]^2}{n}}$$

$$\mathrm{log\_bias} = \frac{\sum[\log(S) - \log(I)]}{n} \qquad (2)$$

These errors estimates have been used in recent literature to describe the performance of the ocean color algorithms (O'Reilly et al., 2000) and to validate SeaWiFS global estimates of Chl (Gregg & Casey, 2004). Note that after logarithmic transformation, these errors cannot be expressed as percentage (Campbell & Feng, 2005).

3. Results and discussion

3.1. Comparison between in situ and satellite data

Fig. 3 and Table 1 show the comparison between in situ Chl based on discrete sample measurements (locations shown in Fig. 2a–c) and satellite Chl derived from the composite data/image for each cruise survey. Overall, both SeaWiFS and MODIS overestimated Chl by 0.119 to 0.290 in terms of log_bias, while log_RMS errors were within 0.30–0.45. The errors are considerably larger before logarithmic transformation, with RMS errors ranging between 112% and 249% and bias errors between 69% and 146%. Moreover, Table 1 shows different regression slopes for the relationship between satellite and in situ Chl among three cruises, especially between the slopes in the TWS and in the northern SCS. This implies dynamic and complex oceanographic conditions at different time and space scales, as well as some uncertainties in both the satellite and in situ data sets.

Fig. 4 and Table 2 show that the agreement between in situ flow-through Chl (locations shown in Fig. 2g–j) and satellite estimates is better than between the satellite and discrete sample data (see Fig. 3). Log_RMS errors are within 0.35 under all circumstances (Table 2). The July 2004 satellite data showed the highest accuracy, with log_bias $<\pm 0.10$ except within the 2-h window. Less bias errors were found for comparisons within <24 h and 48 h, where more matching pairs led to more statistically meaningful results. Similar to the comparison results from the discrete samples, the percentage RMS errors are significantly larger, varying between 61% and 106% for the July cruise. However, except for the 2-h window where large errors were found because a significant portion of the data points are from coastal waters (Figs. 2h and 4), the slopes are close to 1.0, and the intercepts are nearly zero, suggesting that these RMS errors will not cause significant bias in large-scale studies.

During the August 2004 cruise in the southern TWS, errors in both SeaWiFS and MODIS estimates are larger than those found in July 2004, with log_RMS errors >0.3 and log_bias errors >0.20, This is likely due to the extensive turbid coastal waters (depth <30m) encountered (Fig. 2i and j) where most of

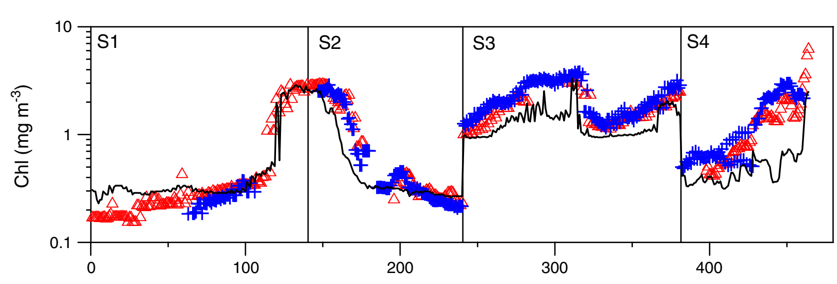

Fig. 5. Chl from in situ flow-through (solid line), SeaWiFS (+), and MODIS (△) along the ship transect lines S1–S4 during the July and August 2004 cruises (Fig. 2). Most of the S3 and S4 data were collected from waters of <30m depth.

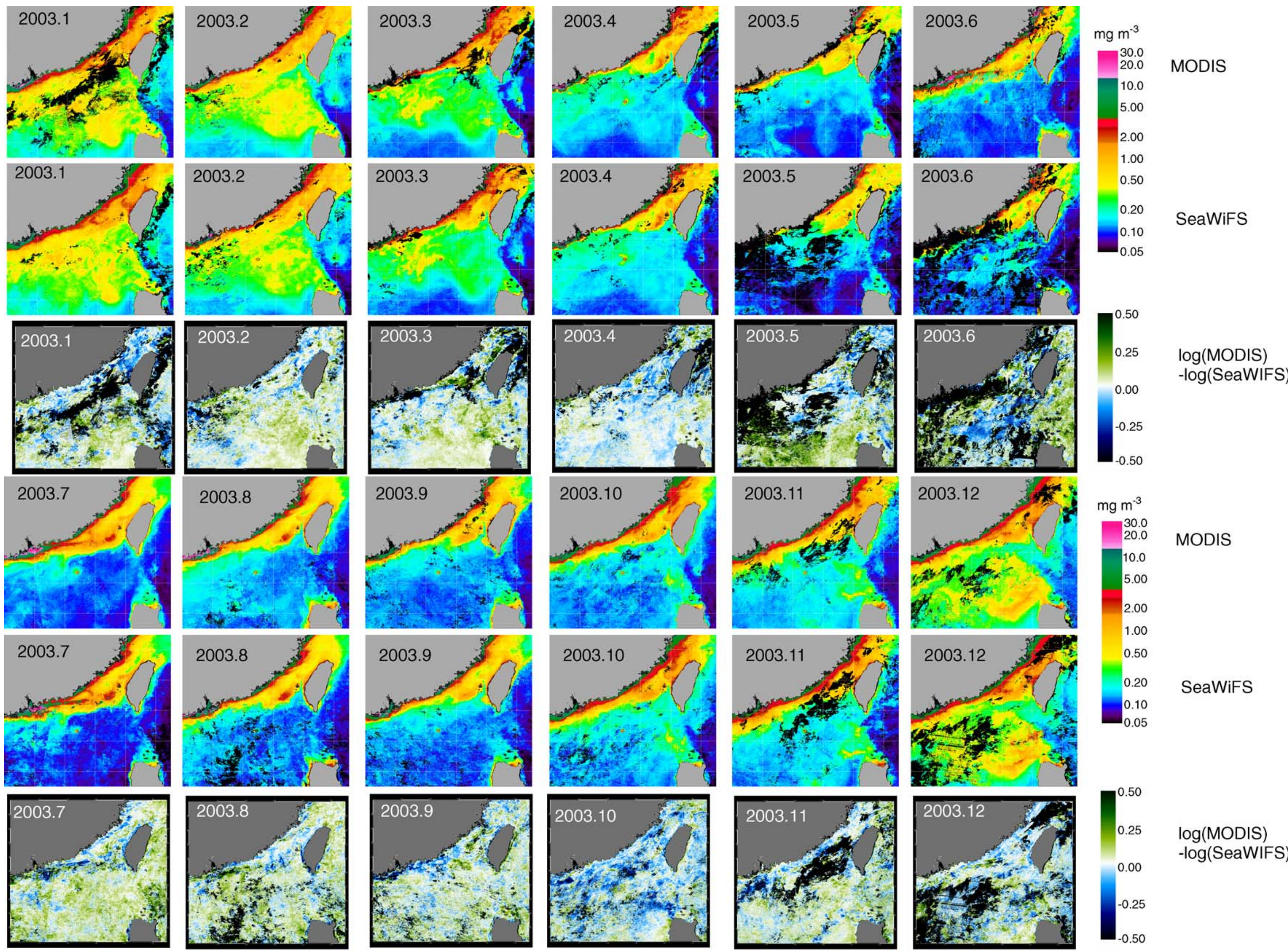

Fig. 6. Monthly average Chl from MODIS and SeaWiFS for 2003, and their corresponding differences.

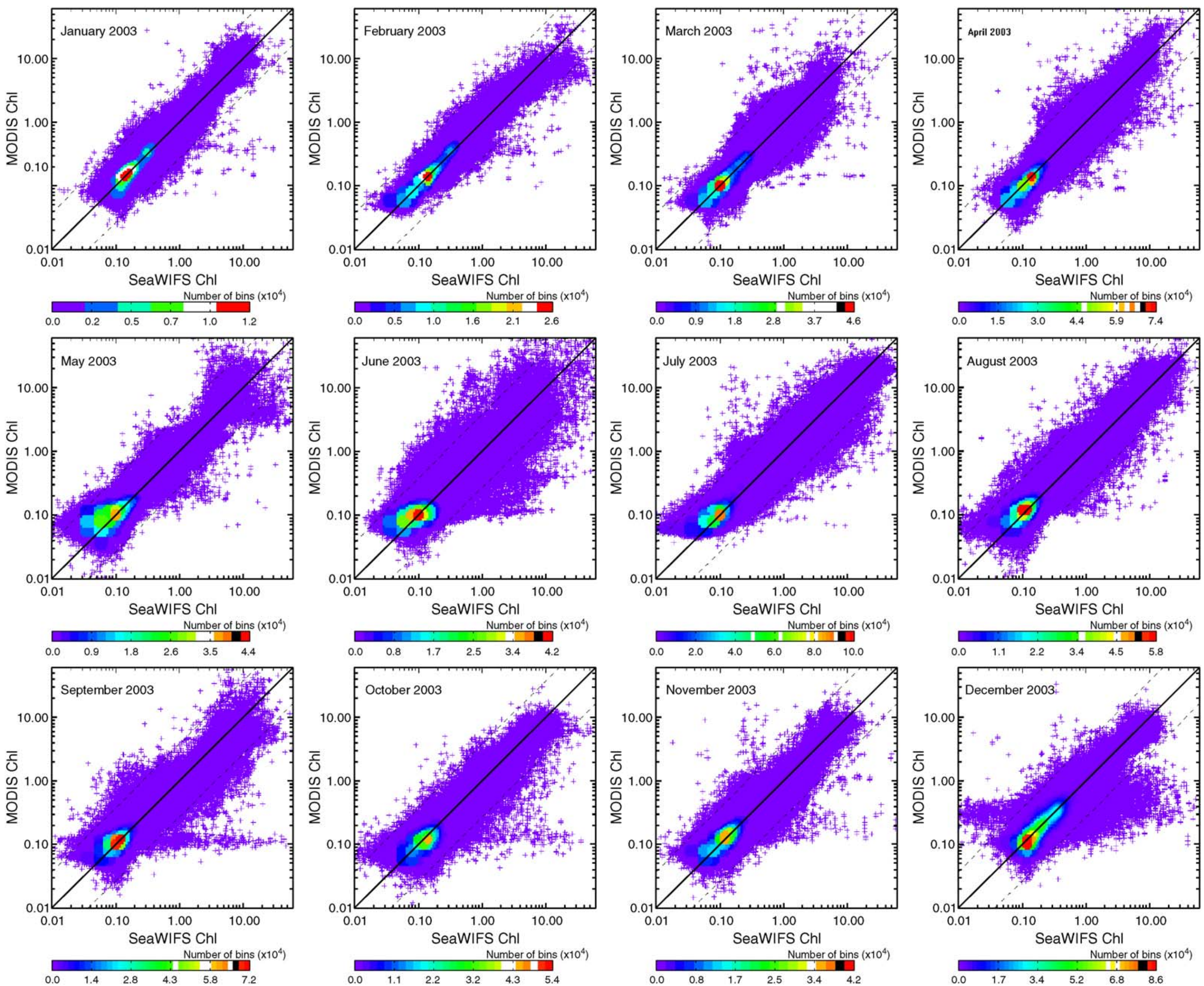

Fig. 7. SeaWiFS versus MODIS Chl for the whole study area (Fig. 6) for 2003. Color scale indicates the density function (histogram).

the Chl values are $>0.3\,mg\,m^{-3}$ (Fig. 4). Consequently, Chl was overestimated (positive bias).

To determine whether the different sensors showed different spatial features, data extracted along the four cruise transects (S1 to S4 in Fig. 2; Table 3) were examined (Fig. 5). Synoptically, SeaWiFS and MODIS Chl data detected nearly identical patterns along the transect lines. These also agreed well with in situ measurements. For transects S3 and S4, satellite Chl estimates were higher than the in situ values because S3 and S4 are in the southern TWS coastal region where enhanced colored dissolved organic matter, suspended sediments loads, and shallow bottom interfered with the satellite algorithms. This result is consistent with those shown in Fig. 4 and Table 2, i.e., errors in coastal waters are generally larger.

MODIS and SeaWiFS Chl estimates are subject to errors from atmospheric correction and bio-optical models, which may partially explain the discrepancies found between satellite and in situ data. The atmosphere over the TWS is often hazy, resulting in larger errors than in regions with clearer atmosphere. The annual mean aerosol optical thickness at 865 nm for the entire TWS, derived from SeaWiFS, is about 0.17 (±0.05, $n=213$ days), compared with a typical value of 0.08 for the North Atlantic. Furthermore, the turbid coastal waters invalidate the near-IR "black pixel" assumption in the atmospheric correction (Hu et al., 2000; Ruddick et al., 2000; Siegel et al., 2000). Although an iterative approach is used to circumvent this difficulty (Arnone et al., 1998; Stumpf et al., 2003), residual errors are likely due to the deviation of the particle backscattering spectral shape (a function of particle size distribution) from that assumed in the model. These errors, combined with those from the imperfect bio-optical inversion model for Chl (i.e., blue/green band ratios), propagate and are magnified in the derived Chl data products. Clearly, more research is needed to improve algorithms in such areas of turbid atmosphere and water.

A second source of error is the discrepancy in time and space between the satellite and in situ sampling coverage. Specifically, the error is due to (1) time difference and (2) sample size. As we pointed out earlier, the time difference between satellite and in situ measurements was relaxed from two hours to several days to obtain enough matching pairs for statistically meaningful comparison. This can create uncertainties in dynamic waters (Balch et al., 1989; Doerffer & Fischer, 1994; Hu et al., 2003). In addition, a satellite pixel is about $1\,km^2$, while the in situ sample represents a much smaller distance or a point at the ship's water intake. Unless the water mass within the $1\,km^2$ is homogeneous, this results in additional uncertainty (Hu et al., 2004). Indeed, one of the reasons why the errors between satellite and flow-through data are smaller than between satellite and discrete-samples is that the time difference is smaller in the former where a median value of all flow-through data covering the same pixel was used to compare with the satellite estimate.

The uncertainty of the in situ measurements may be an additional source of error, especially the uncertainties in the calibrated flow-through Chl data. The flow-through in vivo fluorescence was calibrated to Chl using a uniform conversion factor for the entire region under study. Because of the unknown yet possible variations in fluorescence efficiency, the conversion factor may differ in different waters (Shang et al., 2004b). However, variations appeared to be random in space and time (i.e., there was no systematic error), and thus would unlikely cause bias errors in large-scale comparisons.

The RMS error specified by the SeaWiFS mission goal was <35% in Chl estimates for open ocean waters where the optical properties are dominated by phytoplankton and its direct degradation products (CDOM and detritus) (Hooker et al., 1992; McClain et al., 1998), equivalent to about 0.13 after logarithmic transformation (i.e., log_RMS defined in Eq. (2)). Despite the findings in Gregg and Casey (2004) where log_RMS was incorrectly expressed in percentage to lead to the conclusion that such a goal for the global ocean was generally met, we found that such a claim is still premature because log_RMS errors are much less than the relative (or percentage) RMS errors. Indeed, most of our log_RMS errors are comparable to those reported in Gregg and Casey (2004) for most ocean basins, and much less than those for the Baltic Sea (Darecki & Stramski, 2004), yet our percentage RMS errors are generally between 60% and 100% (July 2004 flow-through data). However, considering the inherent uncertainties in the OC4v4 algorithm itself (log_RMS ~ 0.22, O'Reilly et al., 2000), the large dynamic range (Chl ~ 0.1–10 mg m^{-3}), a large portion of coastal waters in our study region, and the nearly 1:1 slope and small bias, the

Table 4
Statistical results of the monthly Chl data from SeaWiFS and MODIS for the entire study region for 2003

Month	MODIS (mod) vs. SeaWiFS (swf) [range: 0.05–60 mg m^{-3}]								Median		Mean		Mode	
	Slope	Intercept	R	n ($\times 10^5$)	RMS (%)	Bias (%)	log_RMS	log_bias	swf	mod	swf	mod	swf	mod
January	0.93	−0.03	0.95	7.0	32	3.7	0.122	−0.001	0.333	0.352	0.656	0.648	0.143	0.162
February	0.95	−0.01	0.96	8.4	25	6.0	0.099	0.014	0.275	0.301	0.474	0.464	0.125	0.121
March	0.96	−0.01	0.95	7.9	40	8.0	0.118	0.017	0.193	0.201	0.380	0.397	0.103	0.101
April	0.98	−0.03	0.97	8.2	35	−0.7	0.102	−0.016	0.137	0.129	0.364	0.368	0.137	0.129
May	0.85	−0.09	0.94	6.2	41	12	0.138	0.029	0.100	0.110	0.289	0.284	0.080	0.100
June	0.85	−0.10	0.89	6.0	86	15	0.190	0.014	0.115	0.105	0.354	0.348	0.095	0.095
July	0.90	−0.04	0.97	8.6	54	13	0.127	0.037	0.100	0.103	0.512	0.480	0.080	0.093
August	0.92	−0.03	0.96	7.9	40	11	0.125	0.029	0.120	0.130	0.456	0.465	0.110	0.110
September	0.89	−0.07	0.95	8.3	36	6.5	0.127	0.009	0.111	0.116	0.384	0.351	0.101	0.106
October	0.94	−0.08	0.96	8.3	29	−5.7	0.134	−0.043	0.150	0.131	0.513	0.449	0.120	0.111
November	0.92	−0.05	0.96	7.5	41	5.9	0.122	0.008	0.140	0.145	0.476	0.456	0.130	0.135
December	0.90	−0.05	0.93	6.6	40	2.2	0.153	−0.015	0.340	0.333	0.730	0.668	0.120	0.103

performance of SeaWiFS and MODIS observations in the study region may be regarded as satisfactory.

3.2. Comparison between MODIS and SeaWiFS data

MODIS and SeaWiFS Chl data were nearly identical for the three periods examined along specific transects (Figs. 2 and 5). A time-series of monthly mean Chl from July 2002 to October 2004 was also examined. During May and June 2003 the gap in SeaWiFS data is significantly larger than that in MODIS data, probably due to more cloud cover, and also due to changes in SeaWiFS tilt angles with time.

Fig. 6 shows that the monthly spatial patterns of SeaWiFS and MODIS are very similar. Similar spatial patterns occurred also in 2002 and 2004 (not shown here), and the log differences appear to be small (within ±0.1) and random in all nearshore and offshore regions. A quantitative comparison between MODIS and SeaWiFS Chl for the entire study region for 2003 is presented in Fig. 7 and Table 4. On average, about 89% of pixels have relative differences (in log scale) <0.2, and 65% of pixels have relative differences (in log scale) <0.1. These are all smaller than the algorithm "noise" (~0.22, O'Reilly et al., 2000). The relative RMS differences are between 25% and 40% (Table 4) except for a few months where the large difference is apparently due to different cloud coverage (Fig. 6). More importantly, there is not significant bias, as indicated in the slope and intercept values between the two data sets.

Four sub-regions were chosen for further time series analyses: (a) the TWS, with waters <30 m depth excluded; (b) coastal waters (30–200 m); (c) offshore waters (>200 m); d) the Taiwan bank with depths <30 m (Fig. 1).

Monthly mean Chl values and the number of valid pixels used in the mean for these four regions (2002 to 2004) are shown in Fig. 8. Relative difference (i.e., the x term in Eq. (1))

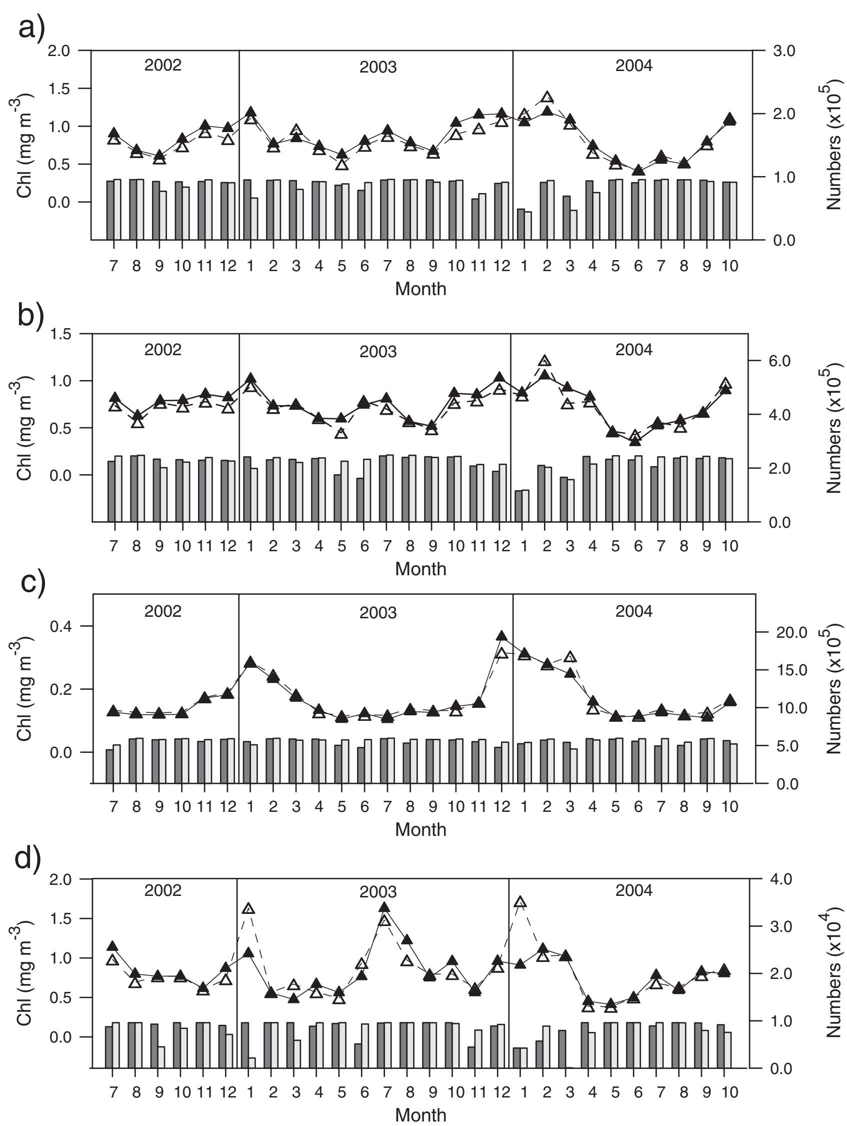

Fig. 8. Monthly average Chl from SeaWiFS (▲) and MODIS (△) for (a) the TWS (data from <30 m waters excluded), (b) coastal region (30–200 m water depth; Fig. 1), (c) offshore region (>200 m water depth), and (d) the shallow Taiwan bank (<30 m). The number of valid (cloud-free, good flags) pixels, after data compositing, used in calculating the monthly mean is also shown in vertical bars for SeaWiFS (dark grey) and MODIS (light grey).

between MODIS and SeaWiFS for most months is <±10%. For the 28 months from July 2002 to October 2004, RMS differences of the mean Chl are 9.8% (TWS, Fig. 8a), 10.7% (20–200 m coastal region, Fig. 8b), 8.4% (>200 m offshore region, Fig. 8c), and 23.4% (Taiwan bank, Fig. 8d), respectively. The corresponding log_RMS differences are 0.044, 0.049, 0.035, and 0.084, respectively. The large difference for January 2003 and January 2004 over the Taiwan bank may simply be due to differences in data gaps between the two sensors (see gaps in Fig. 6).

Other than in January, the seasonal patterns from MODIS and SeaWiFS are very similar for all four regions. The offshore region experiences winter blooms and summer minima. Interannual variation was observed in the TWS and in the 30–200 m coastal waters with more complex hydrological dynamics. In the TWS, the satellite Chl patterns agreed well with the in situ observations, except for the high satellite Chl values seen in winter (e.g., January). Previous studies suggest that low temperatures in winter may limit phytoplankton growth in the TWS (Zhang et al., 1997).

While an in-depth, detailed study of the physical forcing behind these observed patterns is outside the scope of this paper, the spatial and temporal patterns are consistent with existing knowledge based on limited historical oceanographic studies. The summer Chl peak in the TWS is primarily a response to monsoon-driven upwelling, and its magnitude likely depends on the monsoon strength. For example, satellite scatterometer data showed much stronger wind in the TWS in summer 2003 than in summer 2004 (data not shown here), consistent with the higher Chl peak in summer 2003 than in summer 2004. Overall, the seasonal patterns observed between MODIS and SeaWiFS are consistent between sensors.

For most of the months, the number of valid pixels is comparable between MODIS and SeaWiFS. Further, the average percentage cloud cover and the number of satellite overpasses for the TWS are also comparable between the two sensors (Fig. 9), indicating that there is no significant aliasing in calculating the mean (IOCCG, 2004).

To further assess consistency between MODIS and SeaWiFS, two arbitrary transect lines were selected in the north and south of the TWS (Fig. 1), to extract time-series data (Fig. 10). Even when turbid coastal waters are included (satellite-derived Chl > 4 mg m^{-3}) the contour plots suggest similar synoptic and temporal variability between MODIS and SeaWiFS.

The slight differences between MODIS and SeaWiFS data (Figs. 6 and 7) are likely due to differences in sensor design, polarization, band position, overpass time, and band choice in algorithms. For example, one of the atmospheric correction bands (750 nm) for MODIS avoids the oxygen absorption in the atmosphere, while the corresponding SeaWiFS band is centered at 765 nm, covering the entire oxygen absorption and therefore requires more correction. For productive waters, MODIS uses the 488/551 band ratio in the bio-optical inversion while SeaWiFS uses the 510/555 band ratio (O'Reilly et al., 2000).

We recognize that a more rigorous comparison should be performed on the normalized water-leaving radiance data (nL_w) from MODIS and SeaWiFS, because Chl is a secondary product based on nL_w, and is derived using a bio-optical inversion model. However, because most oceanographic researchers are interested in the Chl data and because Chl is a critical parameter for biogeochemical studies as well as for characterizing coastal eutrophication, we focused on comparison of this parameter between the two sensors. Although other bio-optical models exist to estimate Chl (e.g., Carder et al., 1999; Maritorena et al., 2002), the Chl used in this study was derived from a band-ratio algorithm (OC4V4 for SeaWiFS, OC3M for MODIS, see O'Reilly et al., 2000) because it is the default data product

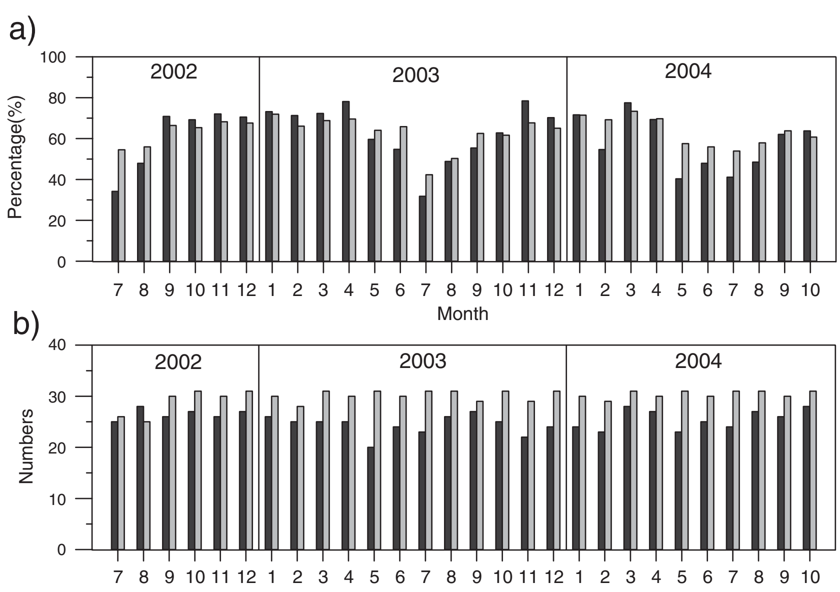

Fig. 9. Average percentage cloud cover in the Taiwan Strait (a) and number of days used in the calculation (b), derived from SeaWiFS (black) and MODIS (grey) from July 2002 to October 2004.

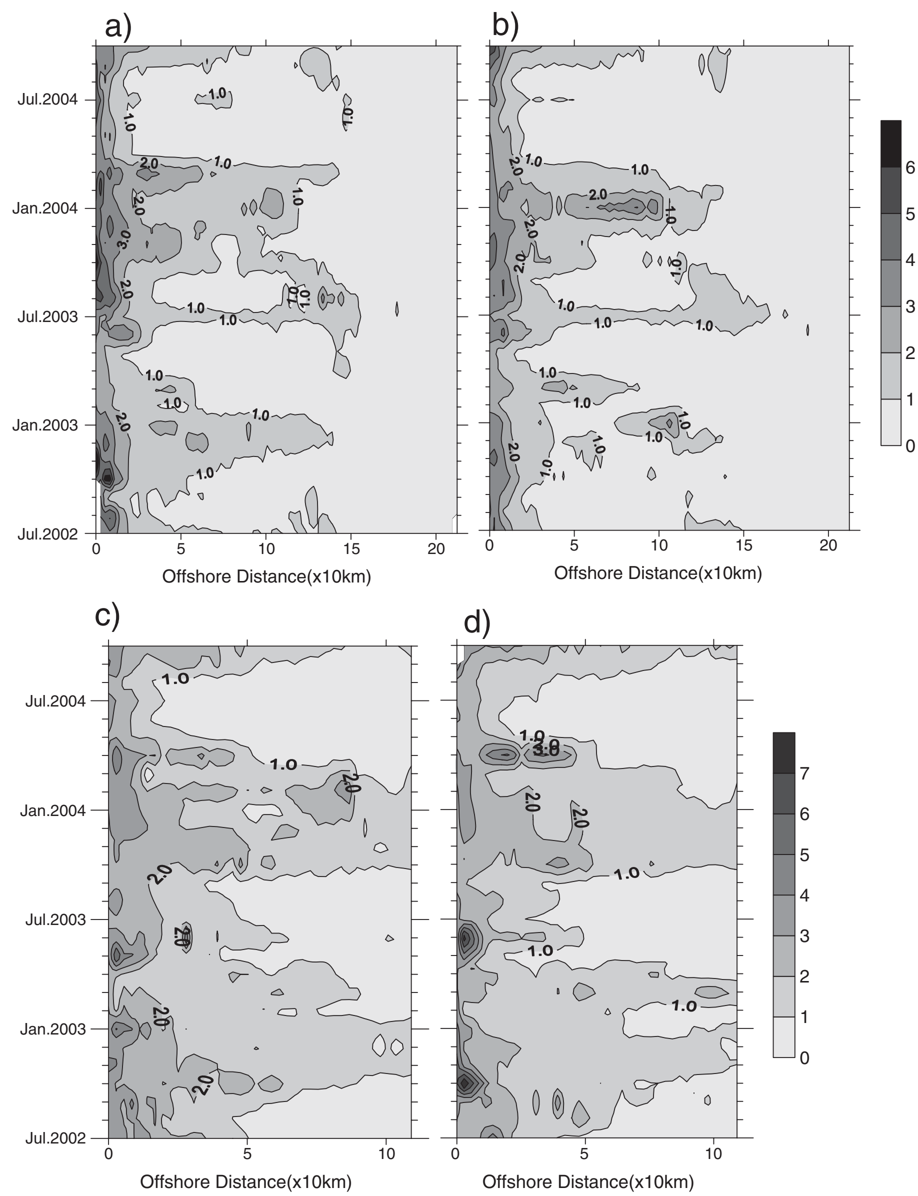

Fig. 10. Cross-shelf Chl transects, as a function of time, from SeaWiFS (a and c) and MODIS (b and d) along the transect lines L1 (a and b) and L2 (c and d) shown in Fig. 1. Numbers are in units of mg m^{-3}.

recommended by NASA and also widely available to the research community.

4. Summary and conclusion

The accuracy and consistency of MODIS and SeaWiFS Chl (mg m^{-3}) estimates for the Taiwan Strait (TWS) and the northern South China Sea (SCS) were assessed using in situ measurements from three cruises during winter and summer 2004. Chl estimates from SeaWiFS and MODIS were then compared for the time frame spanning July 2002 to October 2004.

Both SeaWiFS and MODIS Chl data agreed with in situ measurements, with log_RMS errors (i.e., data transformed in log space) of 0.35 or less for the range of 0.1–10 mg m^{-3}. Slight log_bias errors (up to 0.20) were noted in observations from both sensors for most regions. For coastal regions, where Chl values were >1 mg m^{-3} (July and August 2004 cruises), the log_RMS errors were within 0.35, but log_bias was 0.20–0.30. The corresponding relative RMS and bias errors are much larger, ranging between 60% and 170% and between 0% and 100%, respectively, with errors in coastal waters generally larger than those in the open ocean. These errors may be due to artifacts in satellite data processing algorithms, uncertainties in the in situ measurements, differences in satellite and in situ sampling size and time. However, no significant systematic error was found in the satellite-derived Chl products, as indicated by the nearly 1:1 slope and near-zero intercept between the satellite and in situ data sets for most regions. Further, similar major spatial and temporal distribution patterns were observed by both sensors.

The difference between MODIS and SeaWiFS Chl data is smaller than between satellite and in situ data. The relative differences between the two data sets are generally <±10% for most months. The log_RMS differences in the monthly means between July 2002 and October 2004 from both these sensors for several sub-regions within the study area are less than 0.05 except for the shallow (<30 m) Taiwan bank (~0.08). The corresponding percentage RMS differences are slightly larger, but are <11% for most sub-regions and <24% for the Taiwan bank. The seasonal patterns observed by the two sensors (as well as the statistical results of median, mean, mode) are very similar. In addition, the seasonal patterns of Chl variation for the TWS, for example high Chl in summer owing to upwelling, agree well with those from historical in situ measurements.

Time-series analysis from two arbitrarily selected cross-shelf transect lines showed similar results between the MODIS and SeaWiFS data sets. The slight differences are likely due to different sensor design and processing algorithms, and also possibly due to the time differences between the satellite overpasses (~2 h). On average, cloud-free coverage is comparable between the two sensors, therefore will not create biases during data composition.

In conclusion, except in most shallow (<30m), coastal waters, both MODIS and SeaWiFS retrieved Chl to within 0.35 uncertainty (in log-transformed Chl). Although the relative RMS errors are significantly larger (~60% for open ocean waters to 170% for coastal waters), these estimates are comparable to those found for other global regions and are not significantly larger than the uncertainties in the algorithm used to derive the satellite data product. Further, there is no large systematic error or significant bias in either satellite data set, and MODIS and SeaWiFS Chl are very similar in their absolute values as well as in the spatial patterns. It is therefore possible to use MODIS Chl data in the TWS and its adjacent waters with confidence in the absence of SeaWiFS data.

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