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Global and regional evaluation of the SeaWiFS chlorophyll data set

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Abstract

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll data set was compared to comprehensive archives of in situ chlorophyll data from NASA and NOAA. The global comparison indicated a root mean square (RMS) log error of 31%, with a coefficient of determination (r^2) of 0.76, using 4168 data points where in situ and SeaWiFS data were coincident and collocated. RMS log error for open ocean (defined as bottom depth>200 m) was 27.7% with $r^2=0.72$, compared to 33% RMS log error and $r^2=0.60$ on the coasts, indicating a deterioration of quality of the SeaWiFS data set in coastal regions. All of the Pacific oceanographic basins generally showed very good agreement with SeaWiFS, as did the South Atlantic basin. However, poorer agreement was found in the Mediterranean/Black Seas, Equatorial Atlantic, and the Antarctic. Optical complexity arising from riverine inputs, Saharan dust, and anomalous oceanic constituents contributed to the differences observed in the Atlantic, where an overestimation by SeaWiFS occurred. The Antarctic indicated a pronounced negative bias, indicating an underestimation, especially for chlorophyll concentrations greater than about 0.15 mg m^{-3}. The results provide a comprehensive global and geographic analysis of the SeaWiFS data set, which will assist data users and policy makers in assessing the uncertainty of estimates of global and regional ocean chlorophyll and primary production.

Keywords: SeaWiFS; Chlorophyll; Global and regional evaluation

1. Introduction

Understanding and characterizing uncertainty is a primary goal of national climate planning and implementation activities. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is one of the most important global observational platforms for oceanic biogeochemistry. It has been the primary source of ocean chlorophyll for primary production models (e.g., Behrenfeld et al., 2001, Campbell et al., 2002), ecosystem models (e.g., Moore et al., 2002), coupled physical/biological models (Christian et al., 2002; Gregg, 2002), data assimilation (Friedrichs, 2001, 2002), harmful algal bloom studies (Fisher et al., 2003; Stumpf, 2001), phytoplankton biodiversity (Iglesias-Rodriguez et al., 2002; Kamykowski et al., 2002), biological–physical coupling (Wilson & Adamec, 2002), coral reef studies (Andrefouet et al., 2001), analyses of spatial variability (McClain et al., 2002; Pegau et al., 2002), interannual variability (Leonard et al., 2001; Wiggert et al., 2002) and decadal variability (Gregg & Conkright, 2002; Gregg et al., 2003). Characterizing the uncertainty of the SeaWiFS chlorophyll data set can facilitate a wide variety of applications including policy decisions, modeling, data assimilation, and global and regional scale trend analysis.

The analyses performed here are intended to extend the activities of the SeaWiFS Project, which are restricted to limited comparisons where atmospheric and oceanic optical properties are generally well behaved and understood, using high-resolution Level-2 (calibrated, navigated, derived geophysical products) chlorophyll data. Their focus is on the mission and sensor performance and thus are designed to answer the questions: how good is the calibration, algorithms, and sensor?

While these are essential questions for the analysis of mission performance, it leaves unanswered the question: how good is the data set? To answer this question, we must utilize lower resolution Level-3 (mapped onto an Earth grid) SeaWiFS data that are most often used in scientific applications, and compare against *all* in situ data available. This approach provides information on the

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quality of the SeaWiFS data set as a whole, and when partitioned into regions, defines more precisely where issues arise. This effort represents the first comprehensive and independent analysis of the SeaWiFS chlorophyll data set on a global and regional basis.

2. Methods

SeaWiFS daily mean chlorophyll concentration data were obtained from the NASA/Goddard Earth Sciences (GES)/Distributed Active Archive Center (DAAC). The data used for these analyses were Level-3 global Standard Mapped Images (SMI) of mean chlorophyll at approximately 9-km equal angle resolution from Sep 1997 to Dec 2002. An internet search for publications using SeaWiFS data for scientific oceanographic applications, such as described in the Introduction, indicated that Level-3 data sets were used over lower levels by a ratio of >2:1. This search involved nearly 100 papers where the data type was clearly identified, and excluded papers on subjects of algorithm development and validation, calibration, and data validation. Use of the equal area version of the Level-3 SeaWiFS data produced negligible changes in the results. The data set is

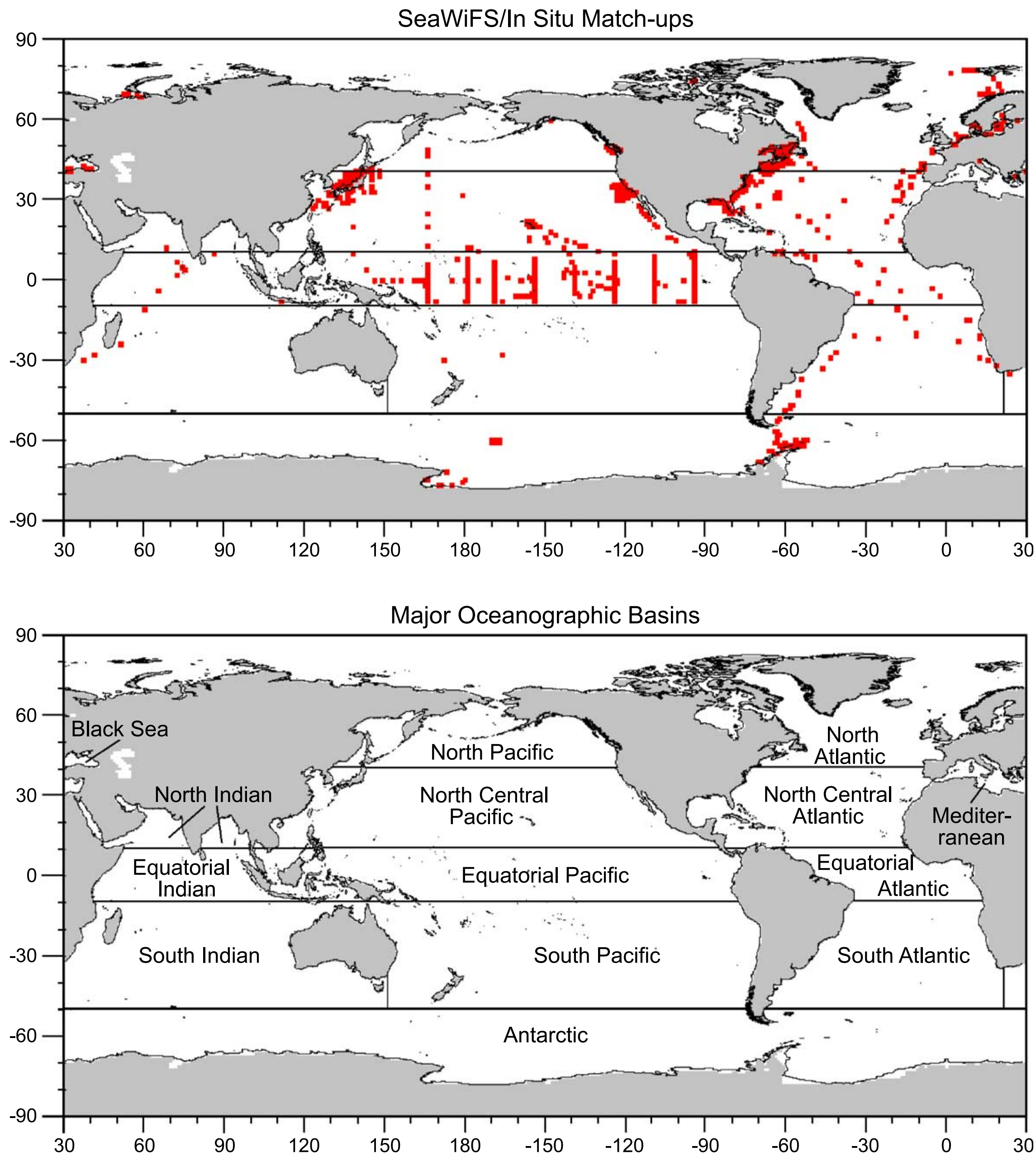


Fig. 1. Top: Global distribution of in situ data that matched with valid SeaWiFS data to within one SeaWiFS Level-3 pixel (approx. 9 km), and within the same day. Bottom: Geographic definition of the 13 major oceanographic basins used in the analysis of the SeaWiFS chlorophyll data set.

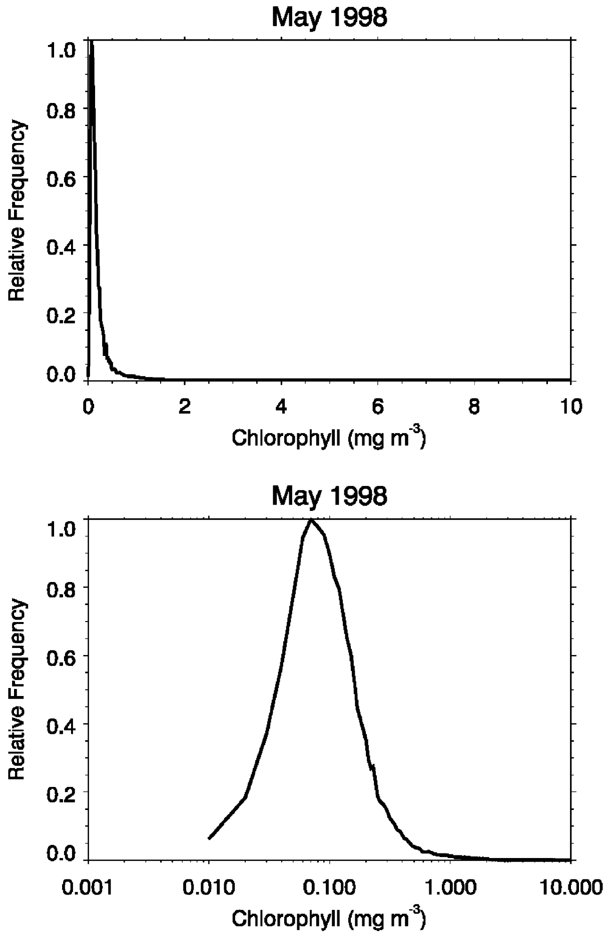


Fig. 2. Top: Frequency distribution of SeaWiFS chlorophyll data for May 1998 in natural chlorophyll units. Bottom: Frequency distribution in log-transformed units.

Version 4, which includes the most recent calibration and processing methodologies employed by the SeaWiFS Project, and was made available to the general public in Aug 2002 (Patt et al., 2003).

In situ chlorophyll measurements were obtained from the NASA SeaWiFS Bio-Optical Archive and Storage System (SeaBASS; Werdell & Bailey, 2002) and the NOAA/National Oceanographic Data Center (NODC)/Ocean Climate Laboratory (OCL) archives (Conkright et al., 2002). These included over 35,700 measurements of fluorometrically/spectrophotometrically derived chlorophyll (mg m^{-3}) at depths of 0–5 m for the SeaWiFS mission period of Sep 15, 1997–Dec 31, 2002.

In situ data that were coincident (occurring within the same day) and collocated (occurring within a single SeaWiFS Level-3 pixel) were averaged. After considering coincident, collocated averages and cloud-free SeaWiFS data, the final result was 4168 comparison match-up points (Fig. 1). For regional analysis of the data, we subdivided the in situ and SeaWiFS data into 13 major ocean basins (Fig. 1). Statistical analyses were performed both globally and within these basins. Both in situ and SeaWiFS data were logarithmically transformed (base 10) before comparison. Analyses included correlation analysis, root mean square (RMS) log error defined as

$$\mathrm{RMS} = \sqrt{\frac{\sum[\log(S) - \log(I)]^2}{n}} \times 100 \tag{1}$$

and average difference defined as

$$\text{Average Difference} = \frac{\sum[\log(S) - \log(I)]}{n} \times 100 \tag{2}$$

where S indicates SeaWiFS chlorophyll, I indicates in situ chlorophyll, and n is the number of samples. The RMS is an estimate of the error of the SeaWiFS data set, the average difference is an estimate of the bias, and the coefficient of determination (r^2) from the correlation analysis indicates the covariance between the data set and the in situ observations. Together, these statistical measures provide information on the performance and uncertainty of the SeaWiFS chlorophyll data set, regionally and globally.

The decision to logarithmically transform chlorophyll data before statistical evaluation is based on the natural distribution of ocean chlorophyll, which is lognormal (Campbell, 1995). Normally distributed data are required for statistical tests to retain their meaning. Otherwise, interpretations of the statistical results can be misleading. For example, the RMS represents the value at which 67% of the data falls within (= 1 sigma). In application of our log-transformed chlorophyll comparisons, we derived an RMS log error of 31.0%. In this case, 76% of the comparisons fell below this error level, which is reasonably close to the definition of the RMS, and supporting the use of the log-transform. When using untransformed data, our RMS contained 95% of the data, which is a major

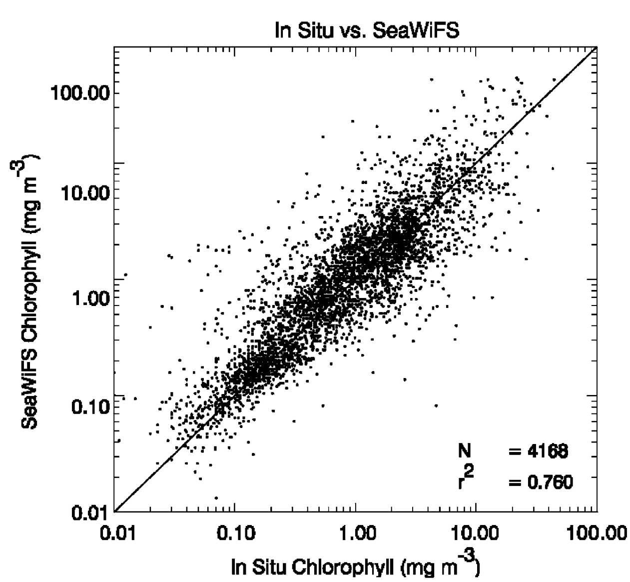
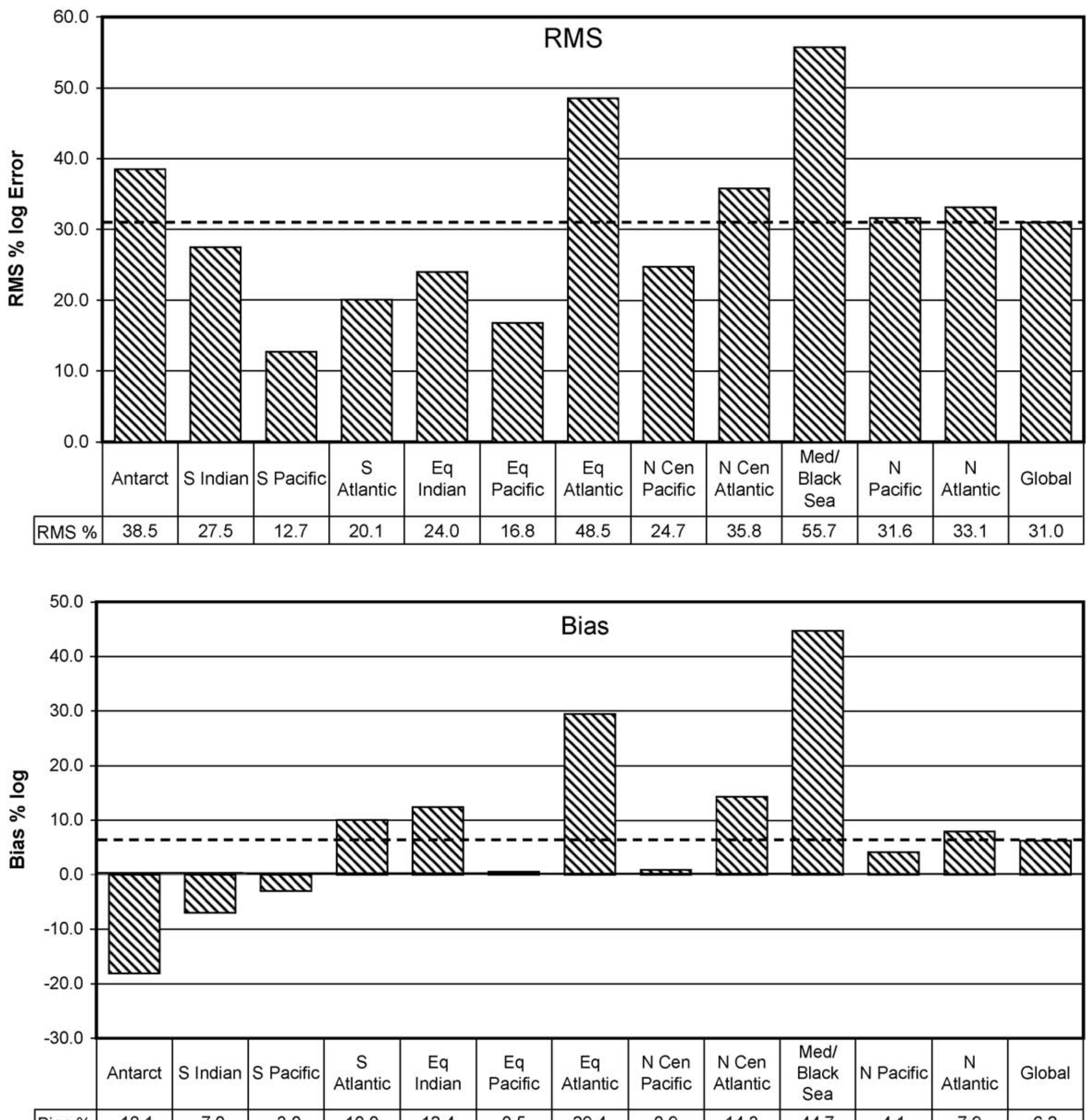


Fig. 3. Scatterplot of in situ data points vs. SeaWiFS Level-3 chlorophyll data, and statistics on the global comparison.

deviation from the expected 67%, strongly suggesting erroneous application of the RMS due to a non-normal data set. Frequency distributions of untransformed and log-transformed SeaWiFS chlorophyll data for May 1998 are shown in Fig. 2.

Finally, we used the blended analysis, where in situ data are merged with SeaWiFS data to remove biases associated with SeaWiFS (Gregg & Conkright, 2001). By taking the difference between the blended fields and the original SeaWiFS data, we can illustrate the problem areas graphically without the constraints of somewhat arbitrary basin definitions. Differences here are reported in untransformed data to provide a different perspective of the error magnitude. This analysis is performed at $1° \times 1°$ longitude/latitude spatial resolution and by season to incorporate sufficient in situ data to affect the analysis. Thus, considerably more in situ data are available than in the point-to-point comparisons.

There are potential space mismatches when comparing 9-km SeaWiFS observations with point measurements obtained from in situ data. This can contribute to the total error in the comparisons. We investigated the magnitude of this error by computing the variability of in situ data located within a single SeaWiFS pixel when multiples existed within the same day. In our global analysis, 70% of the comparisons contained more than one in situ measurement for that day within the same SeaWiFS pixel. The mean standard deviation of log-transformed in situ data occurring within the same SeaWiFS pixel was 0.073 ($\pm$ 0.12). The mean standard deviation fell to 0.053 ($\pm$ 0.08) for the 27% of pixels that contained five or more in situ measurements.



	Antarct	S Indian	S Pacific	S Atlantic	Eq Indian	Eq Pacific	Eq Atlantic	N Cen Pacific	N Cen Atlantic	Med/ Black Sea	N Pacific	N Atlantic	Global
RMS %	38.5	27.5	12.7	20.1	24.0	16.8	48.5	24.7	35.8	55.7	31.6	33.1	31.0

	Antarct	S Indian	S Pacific	S Atlantic	Eq Indian	Eq Pacific	Eq Atlantic	N Cen Pacific	N Cen Atlantic	Med/ Black Sea	N Pacific	N Atlantic	Global
Bias %	-18.1	-7.0	-3.0	10.0	12.4	0.5	29.4	0.9	14.3	44.7	4.1	7.9	6.2

Fig. 4. Top: RMS log error between in situ data and the SeaWiFS chlorophyll data set for the 13 major oceanographic basins, and global. Bottom: Average error or bias. Dashed lines indicate the global RMS log error and bias, respectively.

Considering the global RMS log error of 31%, the standard deviation of 7.3% for in situ data within SeaWiFS pixels suggests that spatial mismatches are not a large contributor to the total error observed here.

Generally, there are 10 main impediments to accurate chlorophyll retrievals from ocean color remote sensing: (1) calibration, (2) presence of chromophoric dissolved organic matter (CDOM), (3) presence of radiance-absorbing aerosols, (4) phytoplankton species diversity, (5) phytoplankton physiology, (6) suspended sediments, (7) clouds, (8) ice, (9) sun glint, and (10) navigation/time space mismatches. In this analysis we ignore calibration, which we assume includes sensor effects such as polarization, scan angle anomalies, etc., as a possible contributor to error because of the recent reprocessing of the SeaWiFS data set. This reprocessing corrected an error in the ocean-based calibration source, that previously led to an incorrect satellite calibration algorithm (Patt et al., 2003). This revision, along with several other more minor modifications (see Patt et al., 2003), produced an improved data set (Casey & Gregg, 2003).

3. Results and discussion

3.1. Global comparison

The overall global comparison of the SeaWiFS data set from Sep 1997 to Dec 2002 indicates very good correspondence (Fig. 3). The coefficient of determination (r^2) is 0.76, which is statistically significant ($P<0.05$). The global RMS error is 31.0% (Fig. 4). This indicates overall good performance of the SeaWiFS data set as compared to in situ data, and is within the mission requirement of 35% RMS (Eplee et al., 2001; Hooker & McClain, 2000; McClain et al., 1998).

These results are not as good as those obtained by the SeaWiFS Project, where 208 in situ SeaWiFS match-up points produced an r^2 of 0.87 and RMS log error = 24% (unpublished SeaWiFS Project analyses). A reduction in performance can be expected when assessing the SeaWiFS data set against comprehensive archives, where 20 times more comparisons are available. Additionally there is an increase of space/time mismatches in our analysis. The SeaWiFS Project analyses use Level-2 (1- and 4-km resolution) data within a few hours of the satellite overpass, while we use Level-3 (9-km resolution) data within 24 h. However, as noted before, this comprehensive global comparison represents an estimate of the performance of the data set, as opposed to the capability of the mission.

In situ data in the Gulf of Maine comprise 41% of the global comparisons, and therefore dominate the global results. When we remove Gulf of Maine comparisons, we obtain global RMS log error = 31.2% with r^2 = 0.795, which is very close to the overall global results.

We divided the global comparisons (including the Gulf of Maine) into those occurring in coastal areas (where bottom depth $\leq$200 m) and open ocean (pelagic) areas (Fig. 5). The open ocean has lower RMS log error (27.7%) and higher r^2 (0.72) than the coasts, where RMS log error = 33.0% and r^2 = 0.60 (Fig. 5).

3.2. Basin-scale comparisons

On an oceanographic basin scale, there are substantial differences in the performance of the SeaWiFS chlorophyll data set (Fig. 4). The North Indian basin has only a single point for comparison and is excluded. We classify these basins according to their RMS and their r^2 in order establish where the SeaWiFS data set performs well and where it does not. A well-performing basin is one that has a low RMS ($\leq$global mean) and $r^2>0.5$ (more than half the variance explained by the relationship with in situ data).

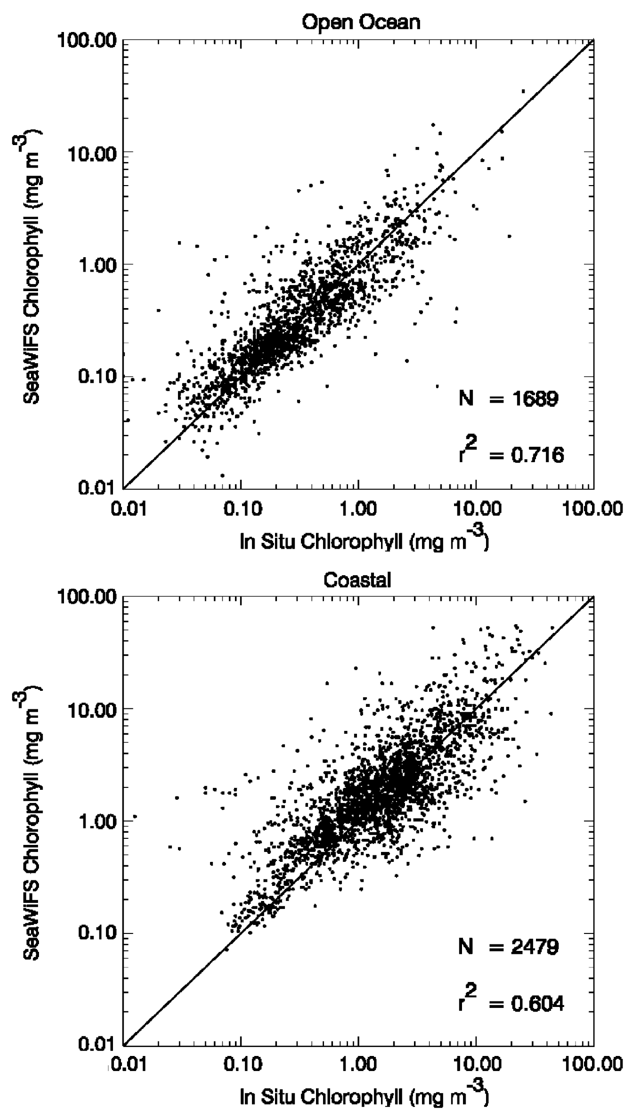


Fig. 5. Scatterplot of in situ/SeaWiFS chlorophyll data divided into open ocean (bottom depth>200 m) and coastal regions (bottom depth$\leq$200 m). The RMS log error on the coast was 33.0%, compared with 27.7% in the open ocean.

3.2.1. Pacific ocean basins

As indicated by the in situ/SeaWiFS chlorophyll data comparisons, the entire Pacific Ocean performed better than or equal to the global mean. Scatterplots of the basin further illustrate the good agreement (Fig. 6). This includes the South Pacific basin which has the lowest RMS of all the oceanographic basins, but there are only two in situ comparisons available. The Pacific can generally be considered free of many of the optical complexities that plague other ocean basins; riverine inputs are minimal and absorbing aerosols are not prevalent except in the western North Central portion.

Comparisons between in situ and SeaWiFS data in the Pacific by other investigators generally support the findings here. Chavez et al. (1999), Kahru and Mitchell (2001), Leonard et al. (2001), and Tang et al. (2003) showed very good agreement in the eastern Equatorial Pacific, the gyre portion of the North Central Pacific, the California Current, and the South China Sea, respectively. However, Bukin et al. (2001) showed substantial overestimates by SeaWiFS in the western portion of the entire Pacific basin at low chlorophyll concentrations (<0.1 mg m^{-3}), while Takashima et al. (2003) observed overestimates in the South Pacific at high concentrations. Our comparisons for the Pacific basins show overestimation by SeaWiFS in the high chlorophyll range as well (Fig. 6). Comparisons by Bukin et al. (2001) at higher concentrations indicated good agreement. Wang and Cota (2003) showed that the SeaWiFS bio-optical algorithm overestimates chlorophyll in the Beaufort and Chukchi Seas, but we have no in situ data in these regions.

3.2.2. Atlantic ocean basins

The South Atlantic not only exhibits the third lowest RMS of the basins, it also has the highest r^2 (0.90; Figs. 4 and 7). The eastern portion of the basin is located near an absorbing aerosol source, the Namib Desert. However, only nine of the 43 observations in this basin occur in the eastern portion, reducing their influence on the basin mean.

The Equatorial Atlantic is one of the most challenging basins for ocean color remote sensing. Proximity to the Saharan Desert, one of the largest sources of absorbing aerosols, compromises atmospheric correction accuracy. In addition, three major tropical rivers (Amazon, Orinoco, and Congo) outflow into the region, and produce plumes visible in ocean color imagery extending well out into the oceanic portions of the basin (Müller-Karger et al., 1988; Signorini et al., 1999). These rivers contain vast amounts of CDOM deriving from terrestrial sources (McClain et al.,

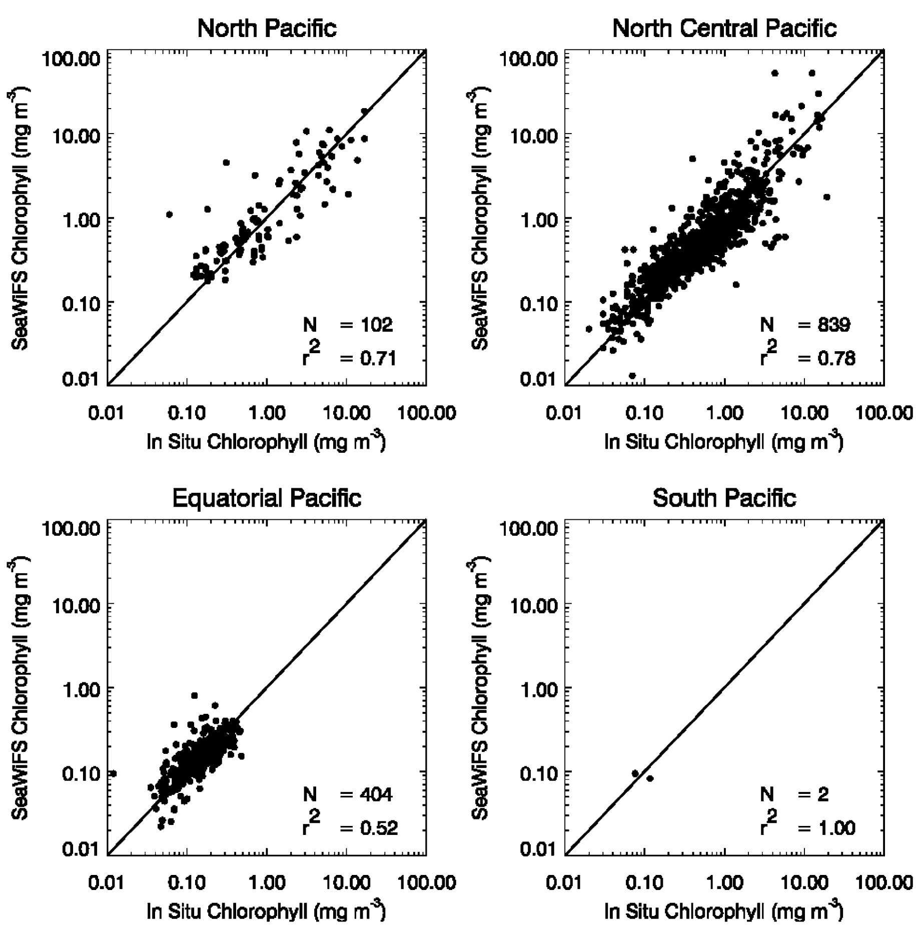


Fig. 6. Scatterplots of in situ data and SeaWiFS chlorophyll data set for the Pacific basins.

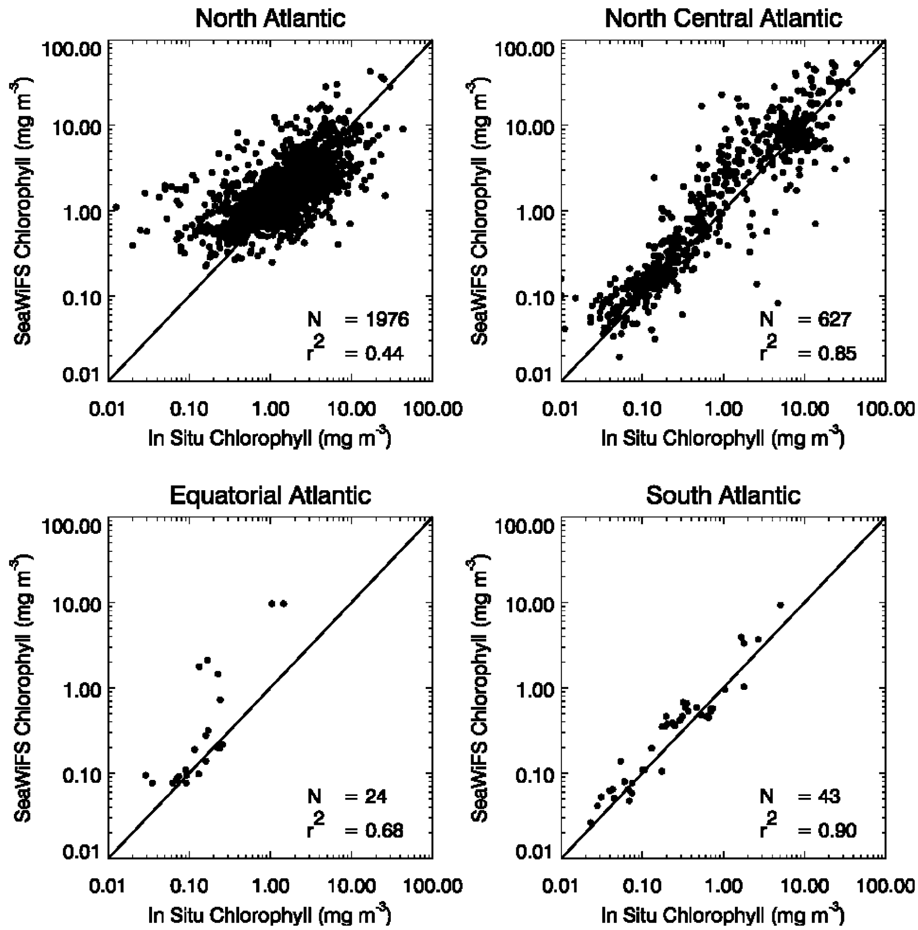


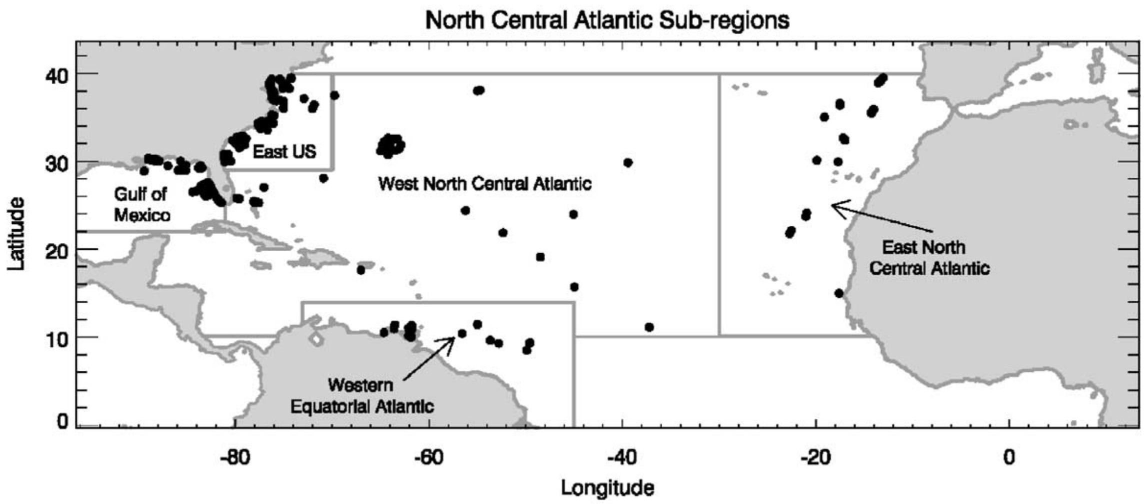
Fig. 7. Scatterplots of in situ data and SeaWiFS chlorophyll data set for the Atlantic basins.

1997). The net effect of both error sources is to cause overestimates of chlorophyll by SeaWiFS, by absorbing radiance in the blue wavelengths. The 48.5% RMS error in the basin observed here is accompanied by a 29.4% positive bias (Fig. 4). The SeaWiFS overestimate can clearly be seen in Fig. 7, which shows increasing overestimates with increasing chlorophyll concentrations. When we remove data located offshore of the northeastern coast of South America, near where the Orinoco and Amazon plumes can be expected, the RMS drops to 22.9%. A 14.1% bias remains, however, which may be related to Saharan dust and/or Congo River influences.

When we evaluate just the areas close to rivers near the South American continent including nearby points considered previously within the North Central Atlantic basin (39 observations total), we observe an RMS error of 64.0% with a very high (49.1%) bias (see Fig. 8). Froidefond et al. (2002a) also found poor agreement between SeaWiFS chlorophyll (using the OC2 algorithm; O'Reilly et al., 1998) and in situ data near the Amazon plume. However, they found a bias only where total suspended sediments were high.

The North Central Atlantic, although ranking fourth worst as a basin in RMS error, exhibits very high r^2 (0.85). This combination suggests a bias, which is indicated in Figs. 4 and 7. This is an optically complex basin. The eastern side is subject to even more intense absorbing aerosol dust plumes from the Saharan Desert than the Equatorial Atlantic. Severe overestimates of SeaWiFS chlorophyll, due to excessive removal of blue water-leaving radiance have been reported here (Moulin et al., 2001). Saharan dust can cross the Atlantic to the eastern US coast and Gulf of Mexico (Goudie & Middleton, 2001; Lenes et al., 2001). The southwestern portion is subjected to outflow from the Amazon and Orinoco rivers (Conkright et al., 2000).

Because of the complexity of the North Central Atlantic, we subdivided it into five subregions (Fig. 8). The portion near the South American coast is discussed above. The Gulf of Mexico subregion has low RMS (28.8%), and high r^2 (0.87), suggesting good performance of the SeaWiFS data set in this area. Nearly all of the data in these comparisons are located in coastal waters. Other comparisons of SeaWiFS and in situ data in the Gulf of Mexico have also shown reasonable agreement, except in the case of a massive dinoflagellate bloom in October 1999 (Vanderbloemen & Müller-Karger, 2001). The US East Coast in situ data have some of the largest values observed in the entire match-up archive, with values >10.0 mg m^{-3} not uncommon. Still the SeaWiFS data set compares very favorably in



	N	r^2	RMS log Error	Bias
Gulf of Mexico	227	0.87	28.8%	17.0%
East US	239	0.65	38.0%	10.0%
West North Central Atlantic	106	0.33	36.2%	8.5%
Western Equatorial Atlantic	39	0.61	64.0%	49.1%
East North Central Atlantic	23	0.53	29.1%	15.3%

Fig. 8. Map of in situ data corresponding with valid SeaWiFS data within the five subregions of the North Central Atlantic basin. Statistics on the subregions are shown below the data locations.

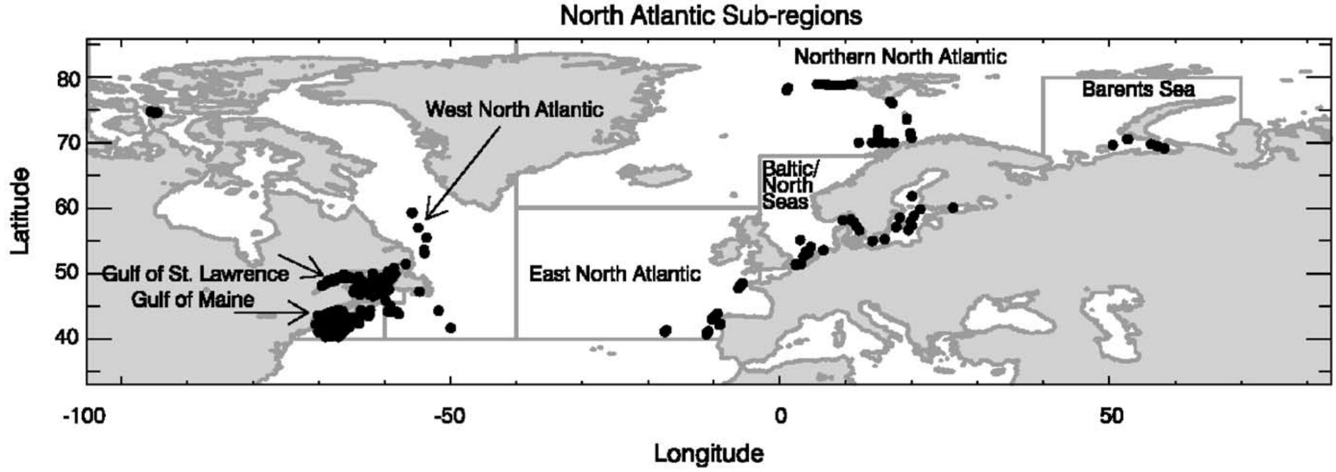
terms of r^2 (0.65), although with moderately high RMS log error (38%).

The eastern portion of the North Central Atlantic basin, comprising data stations offshore of Spain to the Mauritanian coast, exhibits good RMS log error (29.1%) and r^2 (0.53), but a substantial positive bias (15.3%) is found, indicating an overestimate by SeaWiFS. We attribute this to proximity of these stations to the Saharan dust plumes. Davenport et al. (2002) found very good agreement between SeaWiFS and in situ data in this region, just north of the Canary Islands, using data only when no evidence of aerosols could be seen. We derive an RMS log error of 8.4% for their three stations. This supports our assertion that Saharan dust is responsible for the differences between SeaWiFS-derived chlorophyll and in situ data in this region.

Interestingly, it is the central portion of the basin (shown as the West North Central Atlantic in Fig. 8) that returns the poorest agreement. High RMS (36.2%) is accompanied by low r^2 (0.33), although there is low positive bias (8.5%). These results suggest the SeaWiFS data set has large error and poor ability to covary here. This is especially surprising considering that this subregion includes the North Atlantic gyre, which has been used as a calibration/validation area because of low and stable chlorophyll concentrations (Gordon, Brown et al., 1983; Gordon, Clark et al., 1983). In the midst of the gyre one in situ observation of 0.3 mg m^{-3} is much higher than the SeaWiFS estimate of 0.06 mg m^{-3}. Nearby SeaWiFS data are consistent with these very low values while nearby in situ data are about three times lower. We believe this suggests in situ data error, or perhaps transient presence of coccolithophores, which are found in this region (Haidar & Thierstein, 2001). Other in situ data values in the Sargasso Sea and slightly northwest indicate values <0.01 mg m^{-3}, which is below the SeaWiFS data set reporting limits. These anomalous observations are contributors to the poor agreement here.

The North Atlantic contains the most in situ data points of any basin, and consequently the RMS log error is comparable with the global RMS (33.1%; Fig. 4). However, the r^2 is quite low (0.44), indicating that less than half the variance in the SeaWiFS data set corresponds with the in situ record. Like the North Central Atlantic, this basin contains complex bio-optical properties. Unlike the North Central Atlantic, it is generally not impacted greatly by absorbing aerosols and riverine sources of CDOM.

We subdivided this basin into seven subregions (Fig. 9) to try to gain insight into its poor covariance behavior. The Gulf of Maine is numerically predominant and thus drives the relationships. It has about 41% of the global observations, so it is a major contributor to the global statistics as well. It and the Gulf of St. Lawrence have moderate RMS (31.2% and 37.2%, respectively), and biases are low, but relatively low r^2 values indicate a poor ability of the SeaWiFS data set to capture variability (Fig. 9). Although located near the North American continent, neither is predominantly coastal. The Gulf of Maine has been noted for coccolithophore blooms (Ackleson et al., 1994; Matrai & Keller, 1993), which can have substantial effects on



	N	r^2	RMS log Error	Bias
Gulf of Maine	1690	0.46	31.2%	7.1%
Gulf of St. Lawrence	172	0.43	37.2%	7.1%
West North Atlantic	26	0.28	50.7%	24.8%
East North Atlantic	21	0.65	19.7%	8.8%
Northern North Atlantic	28	0.41	44.1%	13.2%
Baltic/North Seas	34	0.02	49.4%	15.5%
Barents Sea	5	0.27	112.2%	109.7%

Fig. 9. Map of in situ data corresponding with valid SeaWiFS data within the seven subregions of the North Atlantic basin. Statistics on the subregions are shown below the data locations.

atmospheric correction. Most likely this and other optical properties inconsistent with the bio-optical algorithm are responsible for the poor covariance.

The Baltic Sea has elevated RMS and very low r^2, indicating no relationship between SeaWiFS data set variability and that of the in situ data (Fig. 9). Darecki et al. (2003) attributed poor performance of SeaWiFS bio-optical algorithms to CDOM. The southeastern Barents Sea subregion indicates clear bias, and very high RMS. In fact, the RMS in the Barents Sea is the highest recorded for any basin or subregion analyzed in this effort. These five points are all coastal, which suggests contamination by drifting, subpixel-scale sea ice undetected in the processing algorithms. Overestimates by the SeaWiFS data set are observed in the eastern Barents Sea, and are consistent with other observations (Burenkov et al., 2001).

The West North Atlantic shows very high RMS (50.7%) and very low r^2 (0.28), along with substantial bias. This poor agreement is predominated by overestimates by the SeaWiFS data set in low chlorophyll concentrations. Cota et al. (2003) showed that the OC4 bio-optical algorithm (O'Reilly et al., 2000) used by SeaWiFS underestimates chlorophyll at concentrations < 10 mg m^{-3} primarily due to the predominance of diatoms and prymnesiophytes. This suggests that atmospheric correction errors produce the overestimates observed here. A similar problem occurs with the Northern North Atlantic. Stramska et al. (2003) indicated that SeaWiFS bio-optical algorithms overestimate at low chlorophyll concentrations and underestimate at high concentrations here, which they suggested was due to predominance by diatoms in these waters.

The only subregion within the North Atlantic basin that does not appear to have major discrepancies between the in situ data and the SeaWiFS data set is the eastern portion, located offshore between the United Kingdom and central Spain. Here the RMS is very low (19.7%) and is accompanied by high r^2 (0.65). Darecki et al. (2003) and Pinkerton et al. (2003) also found good performance of SeaWiFS algorithms and data in the Irish Sea and English Channel, respectively.

3.2.3. Indian ocean basins

The Equatorial and South Indian are two basins that exhibit mixed results in the comparison of the SeaWiFS chlorophyll data set with in situ observations. The low RMS in the Equatorial Indian basin is quite surprising (Fig. 4), considering that this region is near the great absorbing aerosol sources (i.e., the North African and Middle Eastern deserts) and is also subject to pollution (Chung et al., 2002; Satheesh & Srinivasan, 2002). Note that the r^2 for this basin is low (0.32), suggesting poor covariance (Fig. 10). This may be related to the influence of absorbing aerosols because their distribution is different from chlorophyll. However, there are only seven valid observational comparisons, so a conclusive evaluation is not possible.

The South Indian has only five valid comparison points, and indicates low RMS relative to the global mean (27.5%;

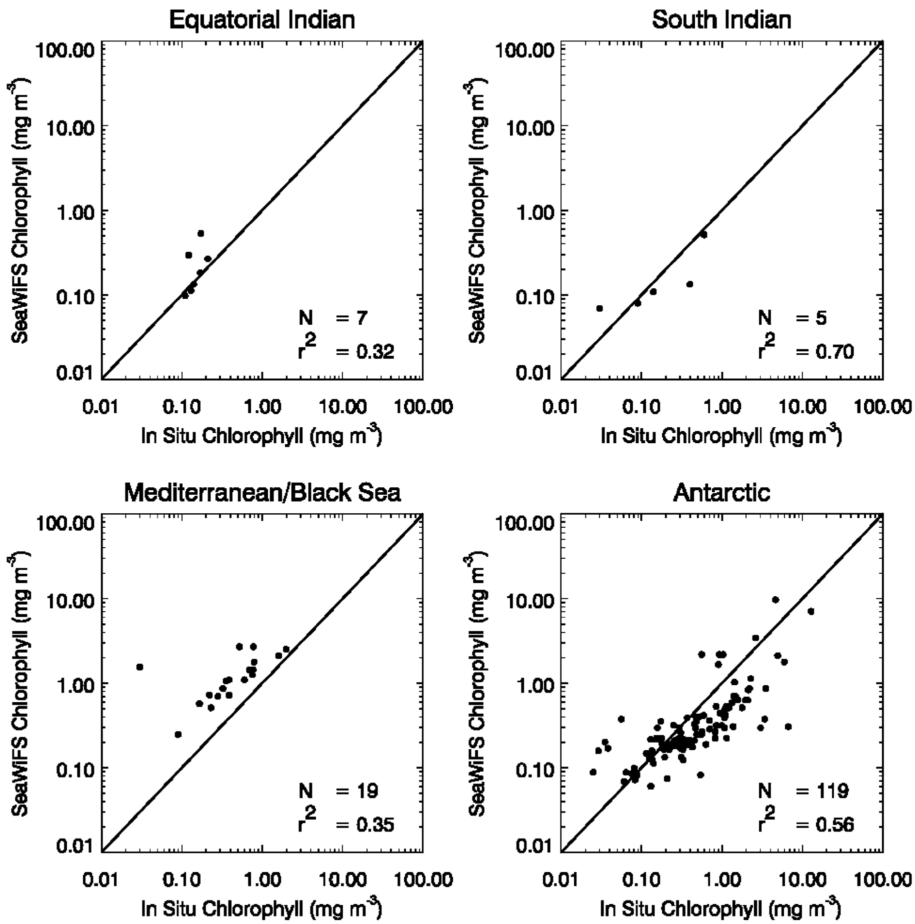


Fig. 10. Scatterplots of in situ data and SeaWiFS chlorophyll data set for the Indian, Mediterranean, and Antarctic basins.

Fig. 4). It has high r^2 (0.70) and small bias, and the covariance is impacted by two outliers (Fig. 10).

3.2.4. Antarctic ocean basin

The Antarctic basin, defined here as poleward of $-50°$ latitude, has high RMS log error (38.5%) and is the only basin that shows substantial negative bias (-18.1%; Fig. 4), indicating underestimate by the SeaWiFS data set. This underestimation trend appears to begin near chlorophyll concentration of about 0.15 mg m^{-3} (Fig. 10). Dierssen and Smith (2000) reported that use of the OC2 bio-optical algorithm (O'Reilly et al., 1998) results in an underestimate in Antarctic Peninsula chlorophyll by about a factor of 2. Although the modern SeaWiFS algorithms use the OC4 bio-optical algorithm (O'Reilly et al., 2000), our results continue to support the assertion by Dierssen and Smith (2000) for the SeaWiFS data set. The moderately high r^2 (0.56; Fig. 10) indicates that the SeaWiFS data set captures most of the variability of data within the basin, however.

A closer look at the Antarctic reveals intrabasin complexities. There are in situ observations that match up with the SeaWiFS data set in three distinct areas of the Antarctic: the Antarctic Peninsula/Drake Passage, the Ross Sea, and the central Pacific sector (Fig. 1). The Drake Passage contains about 60% of the observations and predominates the basin results. Here a large negative bias is apparent, especially for chlorophyll concentrations greater than about 0.15 mg m^{-3}. The correlation indicates high r^2 (0.78; data not shown). The results for this subregion are in conformance with the observations of Dierssen and Smith (2000). The Ross Sea and Pacific sector have much poorer agreement, with almost no covariance between the in situ and SeaWiFS data set ($r^2 = 0.20$ and 0.0, respectively; data not shown). Barbini et al. (2001) found underestimates of SeaWiFS relative to in situ observations as did Moore et al. (1999) in the Pacific sector, using previous versions of the data set. Both found relationships similar to our findings in the Drake Passage, i.e., reasonably good covariance (Moore et al., 1999 showed $r^2 = 0.72$), but an underestimate at high chlorophyll concentrations, with agreement at low values. The Pacific sector comparison is particularly noteworthy in that a very wide range of chlorophyll is reported in the in situ values, which span only a few days time. SeaWiFS, conversely, observed consistent low chlorophyll (about 0.2 mg m^{-3}) during this period. A very large bloom was observed by a series of moorings at this location and time by Abbott et al. (2000), conforming to the in situ data records. These results suggest problems with the SeaWiFS data set in the Antarctic basin as a whole, and especially in some subregions of the basin.

There is an emerging consensus that the bio-optical properties of the Antarctic are substantially different from the global ocean mean. It is established that phytoplankton species compositions are quite different here, with diatoms and *Phaeocystis* spp. predominating in many parts (Arrigo et al., 1999), in contrast to the community composition in the in situ data set used to develop the bio-optical algorithms (O'Reilly et al., 2000). These phytoplankton functional groups have different absorption and scattering properties than other phytoplankton groups (Stramski et al., 2001). In addition, relative concentrations of detritus/CDOM may be different here (Dierssen & Smith, 2000), which can alter the absorption and backscattering properties and produce error in conversion of water-leaving radiances to chlorophyll in the OC4 algorithm. Package effects (e.g., Bricaud et al., 1995) may also be at work. Finally, heavy and persistent cloud cover and presence of ice can create errors in the chlorophyll retrieval if undetected in the SeaWiFS atmospheric correction algorithms. This is a distinct possibility in the Southern Ocean and is a difficult problem to correct if clouds and ice comprise only a part of a SeaWiFS observational pixel. Similar errors in CZCS data were observed by Sullivan et al. (1993) and Mitchell and Holm-Hansen (1991), suggesting that these problems are in fact environmental in nature and not sensor-specific. The Antarctic basin is a challenge for ocean color remote sensing.

3.3. Mediterranean Sea/Black Sea basin

Among all of the basins, the Mediterranean/Black Sea region has the highest RMS for the SeaWiFS/in situ data comparisons (Figs. 4 and 10). A substantial positive bias is apparent as well (44.7%) along with low r^2 (0.35). The SeaWiFS data set clearly overestimates the in situ data in this region across the entire range of chlorophyll observed, from 0.03 to 1.61 mg m^{-3} (Fig. 10). The largest outlier in Fig. 10, where SeaWiFS estimates >1 mg m^{-3} and the corresponding in situ measurement shows the lowest value, 0.03 mg m^{-3}, occurs in the pelagic Black Sea. Observations by other investigators (using previous versions of SeaWiFS data), confirm these findings (Bricaud et al., 2002; Burenkov et al., 2000; D'Ortenzio et al., 2002; Melin et al., 2003). Bricaud et al. (2002) and D'Ortenzio et al. (2002) attributed the overestimates in the Mediterranean to atmospheric correction (in particular, aerosols), while Burenkov et al. (2000) found reasonably good agreement with normalized water-leaving radiances in the Black Sea, suggesting bio-optical algorithm issues. All three suggested CDOM as a contributing influence, with the possibility of coccolithophore presence as well (D'Ortenzio et al., 2002). Cokacar et al. (2001) found high reflectances in the Black Sea due to coccoliths. Anomalous optical properties of the Mediterranean in general suggest that application of a regional bio-optical algorithm may yield better performance (Bricaud et al., 2002).

3.4. Blended analysis

Analysis of seasonal blended chlorophyll, where the in situ data have been merged with the SeaWiFS data set, illustrates the actual locations within the broad oceanographic basin definitions where differences occur, and provides a quantitative estimate of the magnitudes. These results are shown as differences between SeaWiFS chlorophyll and blended chlorophyll for all four seasons in untransformed data (Figs. 11 and 12), which allows a different perspective of the differences. In these plots, a negative difference indicates an underestimate by SeaWiFS (the blended chlorophyll is higher than SeaWiFS due to the influence of the in situ data), and vice versa.

Generally, the results in Figs. 11 and 12 support the basin results. For example, generally small differences are seen in the Pacific basin, despite reasonably good sampling by in situ data. Much larger differences are observed in the Atlantic. Other general observations include a consistent overestimate of the SeaWiFS data set in the Mauritanian upwelling region just west of northwest Africa. This is likely the result of unmasked Saharan dust in the atmospheric correction algorithm. When data exist in or near the river plumes of the Equatorial Atlantic, particularly noteworthy in spring for the Congo River and summer for the Amazon/Orinoco Rivers, a clear overestimate is indicated by the SeaWiFS data set. This is expected in the presence of massive amounts of CDOM deriving from these tropical rivers.

While the Pacific basin at large exhibits good agreement between the SeaWiFS data set and in situ data, a consistent overestimate of the SeaWiFS data set occurs in the East China Sea, Yellow Sea, and Sea of Japan region (Figs. 11 and 12). In situ sampling is quite good in this area, and the underestimate by the SeaWiFS data set appears in every season. High concentrations of suspended matter and CDOM have been found in the discharge of the Yangtze River (He et al., 2000). Dramatic increases in fossil fuel burning in eastern China (Kaiser & Qian, 2002) may also contribute absorbing carbonaceous aerosols, which has a similar effect on ocean color algorithms as desert dust.

The Drake Passage and Scotia Sea regions of the Antarctic basin clearly exhibit an underestimate by the SeaWiFS data set (Fig. 11). The underestimate can be quite large and spatially extensive, particularly in autumn, which conforms to observations in the region (Dierssen & Smith, 2000). In contrast, the Ross Sea area clearly shows an overestimate in the eastern portion in both winter and autumn, but reverses in the western portion. Here, the SeaWiFS data set overestimates in winter but underestimates in autumn. However, north of the Ross Sea and in the vicinity of New Zealand a clear underestimate is apparent.

In situ observations in the Arabian Sea are available only in winter, and clearly indicate an overestimate by the

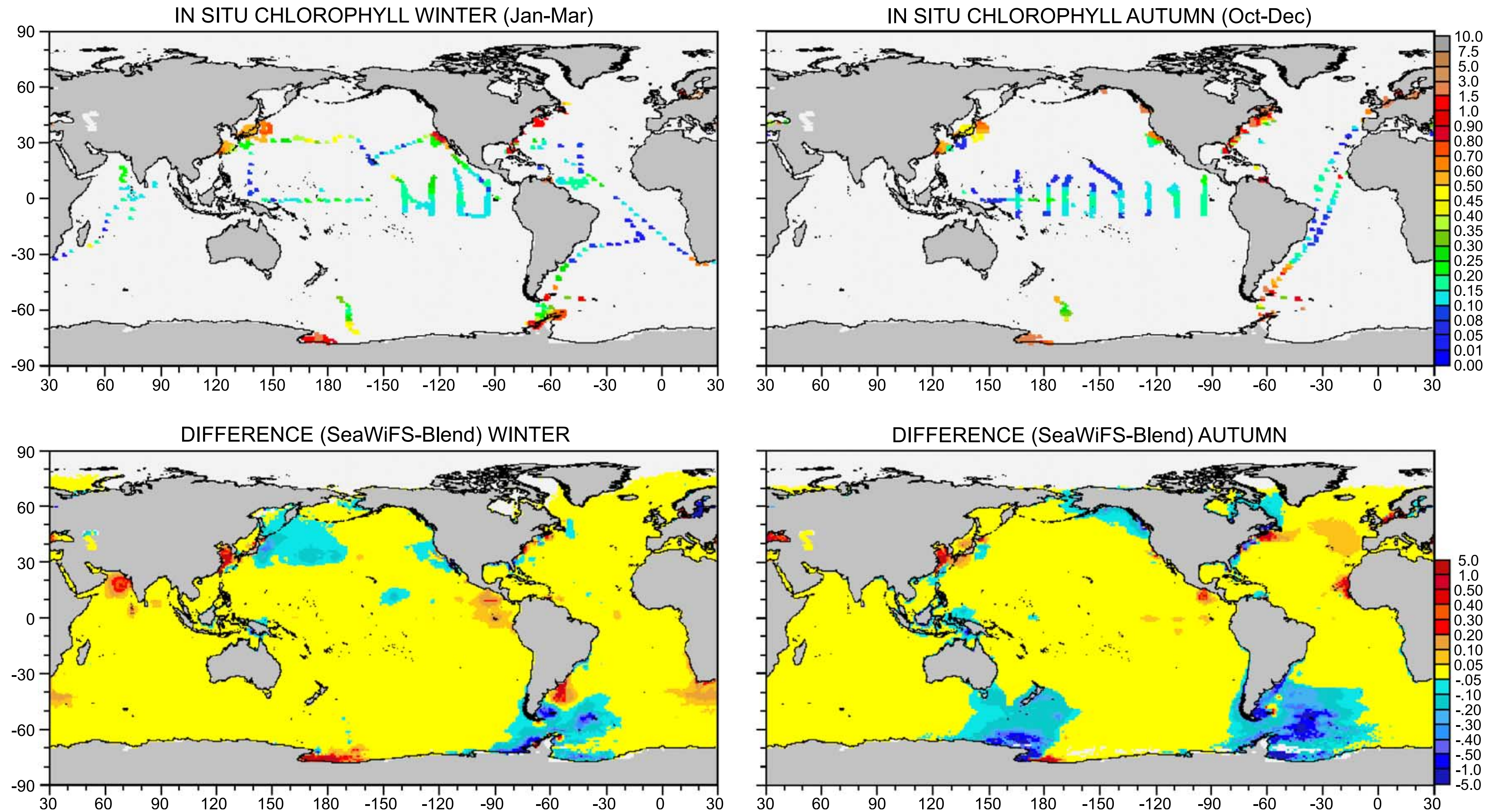


Fig. 11. Difference plot of blended chlorophyll and the SeaWiFS data set for Winter (Jan–Mar) and Autumn (Oct–Dec), illustrating the location and magnitude of differences between the in situ data set and the SeaWiFS data set. The location of the in situ data set is shown above the differences. Differences are expressed as SeaWiFS-blend. A negative difference indicates an underestimate by the SeaWiFS data set, and a positive difference indicates an overestimate. Units are mg m^{-3}.

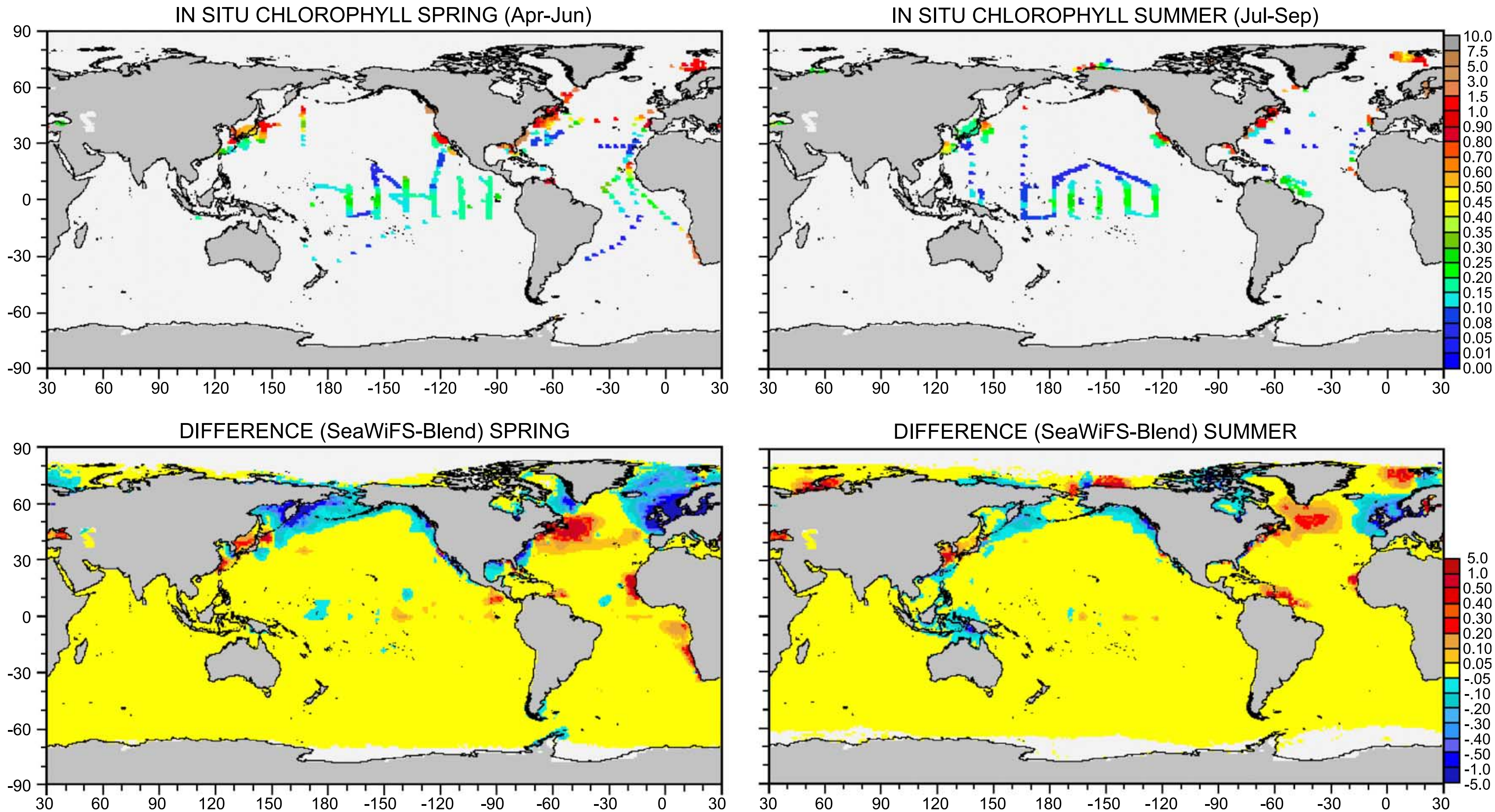


Fig. 12. Difference plot of blended chlorophyll and the SeaWiFS data set for Spring (Apr–Jun) and Summer (Jul–Sep), illustrating the location and magnitude of differences between the in situ data set and the SeaWiFS data set. The location of the in situ data set is shown above the differences. Units are mg m^{-3}.

SeaWiFS data set (Fig. 11). This is consistent with the presence of absorbing aerosols from nearby deserts and/or pollution, but contrary to the point-by-point comparisons in the nearby Equatorial Indian (Fig. 4). However, these results are in conformance with other investigations that indicated a pronounced overestimate of SeaWiFS in the eastern Arabian Sea (Desa et al., 2001). Blending at 1° spatial resolution includes many in situ data values that were not coincident and collocated with valid SeaWiFS data. This enables us to observe a bias that was not previously apparent and supports the viability of the blended analysis comparison here as an additional evaluation method.

Underestimates by the SeaWiFS data set are apparent in the higher latitude portions of the North Pacific, and especially in the North and Baltic Seas. The underestimates in the eastern North Atlantic seas are sometimes very large, particularly in spring and summer (Fig. 12). These results are in disagreement with observations in the English Channel and Bay of Biscay, where overestimates by the SeaWiFS bio-optical algorithms were reported (Froidefond et al., 2002b; Gohin et al., 2002).

4. Summary

A comprehensive global comparison of the SeaWiFS chlorophyll data set and extensive in situ archives from NASA and NOAA indicated a 31% RMS log error, which is below the mission objective of 35%. SeaWiFS data in the entire Pacific Ocean exhibited a very good correspondence with in situ data, as did the South Atlantic basin. Conversely, the Mediterranean/Black Seas, the Equatorial Atlantic, the Antarctic, and parts of the North and North Central Atlantic, showed a poorer comparison. SeaWiFS errors indicated an overestimate in parts of the greater Equatorial and North Atlantic, and the Equatorial Indian, and were likely caused by absorbing aerosols arising from the Sahara and Middle Eastern deserts, as well as excessive CDOM deriving from tropical rivers. The Antarctic basin indicated an underestimate by SeaWiFS, which may have several possible causes deriving from atypical bio-optical properties.

The number of in situ chlorophyll data points available for comparison with SeaWiFS data was quite large and supported quantitative statistical analyses as performed here. The distribution was also quite widespread; all but two of the 13 major oceanographic basins had >2 in situ comparison locations. However, the distribution of in situ chlorophyll was neither systematic nor random. Instead, the data were clustered in certain regions. This clustered distribution has important effects on the global estimates of SeaWiFS uncertainty. For example, >40% of the global data points were located in the Gulf of Maine. This was one of the regions that had a poor comparison between in situ and SeaWiFS chlorophyll. There were also a large number of comparisons located in or near known contaminating environmental substances, most notably CDOM and absorbing aerosols. These effects may have been responsible for degraded performance of SeaWiFS in the Equatorial and North Central Atlantic, as well as the Baltic Sea, among others. In contrast, the South Pacific basin, which is generally free of CDOM and absorbing aerosols, only contained two comparisons. We believe that the net effect of the distribution of in situ/SeaWiFS comparisons leads to an overestimate of the global error, because a disproportionate number are located in regions where ocean color remote sensing contaminants or anomalous oceanic optical properties are present. A more realistic estimate of the error most likely lies between the SeaWiFS Project estimate using relatively pristine data comparisons of 24% and the present one at 31%, and probably tends to be closer to the SeaWiFS Project estimate.

This clustered and possibly biased distribution of in situ chlorophyll data points should be taken into consideration when evaluating the global results. However, our basin-scale analyses remove much of the bias associated with the global analysis, and provides a reasonably reliable estimate of the relative error among the basins, where SeaWiFS data are likely to be accurate and where there may be issues. This is the main purpose of the present paper.

Geographically, problems with SeaWiFS chlorophyll data are largely attributed to the presence of CDOM and absorbing aerosols, according to most investigators and inferentially by the present results. The distribution of these ocean color remote sensing contaminants is very widespread, producing substantial effects over major oceanographic basins. Six of the 12 major basins appear to be affected at least in some portion: Equatorial and North Central, and North Atlantic, Mediterranean, and North and Equatorial Indian. Major improvements in global ocean color remote sensing require identification and removal of the effects of CDOM and absorbing aerosols. There are a few approaches that appear to have achieved at least limited success (e.g., Chomko et al., 2003; Siegel et al., 2002), but a broad consensus has not yet emerged.

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