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Comparison of global chlorophyll climatologies: *In situ*, CZCS, Blended *in situ*-CZCS and SeaWiFS

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Abstract. Chlorophyll climatologies derived from historical *in situ* data, Coastal Zone Color Scanner data (CZCS) and SeaWiFS (Version 3) data were intercompared to evaluate their strengths and weaknesses in representing chlorophyll distributions in the global ocean. A fourth dataset, produced by blending *in situ* data with CZCS data was compared to the other three. Systematic biases were associated with each of these datasets. *In situ* and CZCS data appeared to underestimate chlorophyll since the blended analysis produced generally elevated values. The underestimate by *in situ* data is related to problems mostly in the analysis of the data. CZCS underestimates are related to calibration and algorithm problems. The SeaWiFS data for the open ocean appears to be valid since its within 10% of the blended climatology for all seasons except winter. In the coastal ocean, SeaWiFS may overestimate chlorophyll with values 30–77% higher than the next closest climatology. Blending of *in situ* and satellite may produce the best climatology. This method takes advantage of the higher quality of *in situ* data, and the spatial variability of satellite sensor data. The blended method may be of greatest use for SeaWiFS in coastal areas, where the algorithm problems are greatest.

1. Introduction

What is the distribution of chlorophyll in the surface ocean? The concentration of chlorophyll *a*, (hereafter chlorophyll), the dominant photosynthetic pigment in phytoplankton, is widely used as a proxy for phytoplankton abundance and biomass (Strickland 1965). Accurate chlorophyll data are critical for determining the magnitude and variability of global ocean primary production, the effect of biological processes on carbon dioxide drawdown in surface waters and for improving our understanding of phytoplankton dynamics in the oceans.

There are three comprehensive global chlorophyll climatologies generally available: an *in situ* archive from 1957–1998 maintained by the National Oceanographic Data Center/ Ocean Climate Laboratory (NODC/OCL), the Coastal Zone Color Scanner (CZCS) dataset spanning the time period 1978–1986 and the Sea-Viewing

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Wide Field-of-view Sensor (SeaWiFS) dataset dating from 1997 to the present. The latter two datasets are maintained by the NASA/Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC). Conventional *in situ* chlorophyll methods (e.g. ships, buoys) typically provide high quality, accurate data but are limited in time and space due to the expense of sea operations and the large areal extent of the ocean. The CZCS provided repeat, albeit irregular, observations of global chlorophyll distributions (Feldman *et al.* 1989). After an 11 year gap, the SeaWiFS sensor was launched in 1997 and has provided routine estimates of global chlorophyll distributions (McClain *et al.* 1998). Satellite ocean colour data, while providing incomparably high frequency temporal and spatial data, are subject to cloud obscuration and contamination by excessive sun glint and are generally considered inferior in quality compared to *in situ* data. A fourth dataset, produced by combining *in situ* data with CZCS data using the blended analysis of Reynolds (1988) has been developed for the CZCS era in an attempt to ameliorate some of the adverse effects of satellite sensor data while preserving its spatial variability (Gregg and Conkright 2001). The Ocean Color and Temperature Scanner (OCTS) data are not included here because of its short lifespan (9 months, from November 1996 to June 1997) nor are the Moderate Resolution Imaging Spectrometer (MODIS) data (launched December 1999).

This article compares seasonal surface chlorophyll climatologies derived from all available satellite ocean colour data (CZCS and SeaWiFS), *in situ* data (Conkright *et al.* 1998a), and the blended *in situ* and CZCS dataset (Gregg and Conkright 2001). Although these climatologies are based on different methods and cover different time periods, it is important to compare them. Accurate measurements of chlorophyll concentrations are crucial for global primary production models (Antoine *et al.* 1996, Behrenfield and Falkowski 1997, Iverson *et al.* 2000) which utilize chlorophyll as a primary independent variable. Accurate estimates can improve our knowledge of fluxes of CO_2 into and out of the oceans (e.g. Chavez *et al.* 1999). Ocean biogeochemical models use these various datasets to validate their results (Oschlies, 2000, Gregg 2001, Moore and Doney 2001). An evaluation of the problems associated with each data source, will yield greater understanding of the modeling results.

2. Methods

The following section describes the data and methods used in computing chlorophyll climatologies for *in situ*, CZCS, SeaWiFS, and blended *in situ*/CZCS data. For each dataset, seasonal global and regional area-weighted statistical means were computed. Seasons are defined based on the Northern Hemisphere convention of winter (January–March), spring (April–June), summer (July–September) and fall (October–December). The regions used to compare these data are: subarctic North Pacific and North Atlantic (defined as north of 40°N), North Central Pacific and Atlantic representing the gyres (defined as 10°N–40°N), equatorial basins (defined as 10°S–10°N), North Indian Ocean (north of 10°N and excludes the Persian Gulf), the Southern Ocean (defined as 50°S–90°S) and the South Indian, Pacific and Atlantic Oceans (defined as 10°S–50°S).

2.1. *In situ chlorophyll data*

The historical *in situ* chlorophyll data used in this study were published as part of *World Ocean Database 1998* (WOD98) (Conkright *et al.* 1998a). This dataset includes chlorophyll data compiled by NASA/GSFC, Bedford Institute of

Oceanography, Rosensthiel Marine Laboratory, University of South Florida, International Council for the Exploration of the Seas, as well as data from projects such as the Joint Global Ocean Flux Studies (JGOFS) including the Hawaiian Ocean Time and Bermuda Atlantic Time Series stations (HOT and BATS), Eastern Tropical Pacific (EASTROPAC), California Cooperative Oceanic Fisheries Investigation (CalCOFI) and the Surveillance Trans-Océanique du Pacifique Program of the Centre ORSTOM de Nouméa, New Caledonia (SURTROPAC). SURTROPAC was a monitoring program based on surface chlorophyll measurements carried out by ships of opportunity from Nouméa to Panama, North America, and Japan (Dandonneau 1992).

Chlorophyll has historically been sampled more frequently in spring (44 685 observations), followed by winter (37 288 observations), summer (38 469) and fall (32 492 observations). Table 1 shows the number of *in situ* observations in each basin examined.

The data were quality controlled based on the methods described in Conkright *et al.* (1998a). These methods included range check of values as a function of basin and depth, a check for gradient inversions and excessive gradients, a statistical check and a final check for unrealistic values based on the objective analysis of the data. Data were interpolated to standard levels using 3 or 4 point Lagrangian interpolation (Reiniger and Ross 1968), binned to one-degree latitude-longitude squares, and the mean and standard deviation computed. The results presented here are the output from the objective analysis scheme described by Conkright *et al.* (1998b) and based on Levitus (1982). Briefly, all standard level surface data were first zonally averaged in each one-degree latitude belt by individual ocean basin to provide the first guess-field for the annual analysis at the sea surface. The annual analysis was then used as the first-guess field for a seasonal analysis. The annual analysis was then re-computed from the four seasonal analyses and used as the first guess for the final seasonal analyses. In areas where the data coverage is sparse, the analysed field is the first-guess field (e.g. the all-data annual mean value). This procedure results in smoother seasonal means and reduces the amount of bias due to lack of geographic or seasonal coverage since these areas will not contribute to the annual cycle (Levitus

Table 1. Percentage of one-degree latitude-longitude squares which contain *in situ* measurements. These values are for both coastal and open ocean basins. Numbers in parenthesis indicate the number of observations for each basin.

Region	Winter		Spring		Summer		Fall	
N. Atlantic	2.2	(5973)	7.9	(13 433)	7.8	(11 993)	3.0	(6774)
N. Pacific	3.3	(920)	6.2	(2705)	7.4	(3409)	2.3	(1142)
N. Cent Atlantic	5.4	(1986)	8.6	(9248)	6.2	(2053)	6.1	(3398)
N. Cent Pacific	20.5	(11 680)	22.7	(5931)	24.0	(6561)	23.4	(4911)
N. Indian	7.6	(296)	8.8	(412)	7.3	(449)	5.4	(247)
Eq. Atlantic	9.6	(518)	4.6	(341)	13.7	(798)	2.5	(154)
Eq. Pacific	33.6	(4959)	31.3	(4227)	41.0	(5329)	42.9	(5800)
Eq. Indian	11.2	(554)	19.4	(982)	13.0	(404)	9.2	(264)
S. Atlantic	1.8	(113)	1.5	(86)	0	(1)	1.2	(47)
S. Pacific	27.8	(7298)	22.1	(6790)	24.3	(7068)	25.4	(7320)
S. Indian	8.0	(564)	4.2	(253)	4.3	(258)	4.9	(493)
Southern O.	5.3	(2427)	0.9	(277)	0.6	(146)	3.4	(1942)
Total	9.3	(37 288)	9.0	(44 685)	9.7	(38 469)	8.9	(32 492)

1984). A gridpoint for which less than four observations contributed to the analyzed value at that gridpoint is indicated by an 'x' in all figures. Surface is defined as 0 m–5 m depth.

Data for all years (1955–1998) were used in preparing the seasonal *in situ* climatology. Global and regional statistical means were computed only for areas where a gridpoint contained *in situ* observations.

2.2. *CZCS dataset*

Monthly climatological CZCS pigment (chlorophyll + phaeopigments) means were obtained from the GSFC/DAAC for the entire life of the sensor, October 1978 to June 1986. Pigment estimates were converted to chlorophyll using O'Reilly *et al.*(1998):

$$\log_{10}S = (\log_{10}P - 0.127)/(0.983) \qquad (1)$$

where S indicates satellite-derived chlorophyll and P indicates satellite-derived pigment. Seasonal climatologies were then created by combining each individual year into seasons and then averaging the seasons. This relationship generally agrees with the constant adjustment factor provided by Balch *et al.* (1992), except that it accounts for the covariance of detrital materials (e.g. phaeophytin) with chlorophyll (Gordon *et al.* 1988).

2.3. *Blended dataset*

In situ and satellite sensor data were merged using the blended analysis of Reynolds (1988) with modifications outlined by Gregg and Conkright (2001). The blended analysis involves two components: (1) *in situ* data insertion; and (2) modification of the satellite data field to conform to the *in situ* data values using Poisson's equation (see Reynolds 1988, Gregg and Conkright 2001). This analysis provides a correction for bias in the satellite sensor data and prevents the overwhelming of *in situ* data with the vastly larger number of observations by satellites, while retaining the character of the *in situ* data (which serve as internal boundary conditions). The method conforms to the spatial variability of the satellite field. The *in situ* data used in the blended analysis were the quality controlled unanalysed (no objective analysis) 1×1 degree chlorophyll mean values (Conkright *et al.* 1998b) for years 1978–1986.

Modifications to the Reynolds blended analysis were required due to the large spatial and inter-annual variability of ocean chlorophyll. Some of the modifications applied are: (1) log-transformation of the data to reduce the influence of *in situ* observations across physical-biological-geographical domains (data are transformed back to natural units after blending); (2) confining the blended analysis within four chlorophyll domains (high biomass and low biomass, equatorial upwelling areas, and Amazon river discharge); and (3) application of an Inter-Annual Variability (IAV) correction to reduce discrepancies in the temporal *in situ* to satellite sensor data match-ups. This correction is computed by averaging year-by-year *in situ* and satellite anomalies in the seasonal data for the entire record. Then *in situ* data are inserted into the seasonal climatology as anomalies from CZCS chlorophyll data (Gregg and Conkright 2001). The IAV correction can also ameliorate the effects of sensor degradation in the CZCS lifetime (e.g. Evans and Gordon 1994) by matching *in situ* observations with CZCS degradation state.

2.4. *SeaWiFS data*

The GSFC/DAAC Level-3 SeaWiFS data, for the period October 1997–June 2001 were averaged to a one-degree resolution and used to compute seasonal averages applying the same methods used for CZCS (e.g. creating the seasons for each year individually, and then averaging these). The dataset is Version 3, which incorporates many corrections to deficiencies that were noted in the previous processing versions, such as modifications for water-leaving radiances at near-infrared bands, chlorophyll retrieval, spectral foam reflectance and calibration (McClain *et al.* 2000).

3. Results

3.1. *Comparison of global mean chlorophyll distributions*

The global chlorophyll seasonal patterns of highs and lows are generally consistent among these datasets, although some differences occur (figure 1(a) and table 2). For *in situ* and blended data, the maximum chlorophyll concentrations are observed in the spring (April–June), CZCS chlorophyll peaks during the fall (October–December) and SeaWiFS in the summer (July–September). The lowest global mean concentrations are found in the winter (January–March) for all but the *in situ* data.

SeaWiFS chlorophyll is highest in the global ocean when compared to *in situ*, CZCS and blended chlorophyll for all seasons (figure 1(a) and table 2). *In situ* data chlorophyll is lowest for all but the spring season (April–June) when CZCS chlorophyll is lowest. CZCS and the blended dataset are intermediate between these two extremes, with the blended always higher than the CZCS. Differences between global *in situ* and SeaWiFS chlorophyll range from 32% in spring (April–June) to 93% in fall (October–December). *In situ*/CZCS differences range from 13% in spring (CZCS lower) to 42% in fall (CZCS higher). Blended chlorophyll is higher than both CZCS (8%–34%) and *in situ* chlorophyll (10%–54%). The blended analysis used unanalysed mean values which are higher than the analysed mean values. Point-by-point analyses show that the root mean square (rms) difference between the blended chlorophyll analysis and the CZCS is 52%–70% globally by season, the rms between *in situ* and CZCS is about 82% for each season, rms differences between *in situ* and SeaWiFS are between 32%–54%. Standard deviations (shown in table 2) range from 0.26–0.51 for *in situ* data to 0.91 to 1.1 for SeaWiFS data, the blended and CZCS standard deviations both are between the minima and maxima, ranging from 0.55 to 0.70.

Variances differ greatly among the datasets (figure 1(b)). SeaWiFS variance is 2 to 3 times greater than the CZCS. The CZCS, in turn, has about 1.3 to 8 times the variance of the *in situ* dataset. The blended data variance is only slightly larger than the CZCS.

Figure 2(a) shows spring (April–June) distribution of ship observations with heaviest sampling in the central Pacific and a lack of data in large areas of the oceans such as the Atlantic and Indian central gyres. Also shown in this figure are climatologies for *in situ* (figure 2(b)), CZCS (figure 2(c)), and difference between *in situ* and CZCS (figure 2d). The hatched areas in figure 2b indicate there are either no data or insufficient data for analysis in that grid (fewer than four observations). Hatched areas are widespread in the North Atlantic gyre, the South Pacific, South Atlantic and South Indian Oceans. White areas, in figures 2(c) and (d) indicate no satellite observations are available for that region. Note that despite eight years of observations from CZCS, there are gaps in the data, particularly in the South Pacific Ocean. Blended and SeaWiFS chlorophyll, and differences between *in situ*/blended

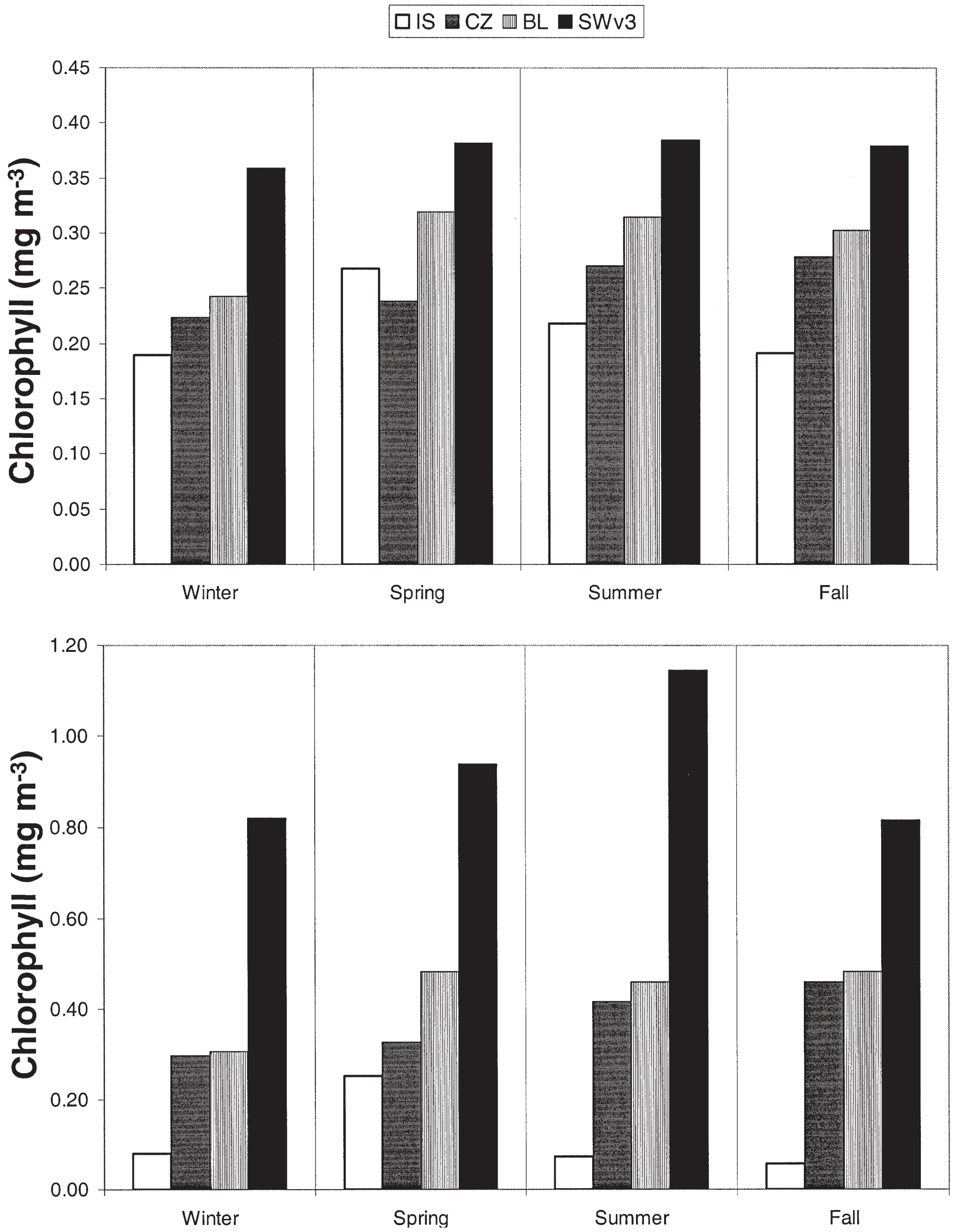

Figure 1. Comparison of global chlorophyll (mg m^{-3}) by season for *in situ*, CZCS, blended analysis, and SeaWiFS data. The top panel (a) shows the global chlorophyll means, the bottom panel (b) shows the global chlorophyll variances.

and *in situ*/SeaWiFS, are shown in figure 3. All four climatologies agree in the general spatial distribution of chlorophyll, i.e. high concentrations at high latitudes and coastal regions, and low concentrations in the mid-latitudes associated with the subtropical gyre systems.

Table 2. Global chlorophyll mean, standard deviations, and variances for the open/coastal ocean, open ocean and coastal oceans.

Data	Winter (January–March)		Spring (April–June)		Summer (July–September)		Fall (October–December)	
	Mean ± S.D.	Variance	Mean ± S.D.	Variance	Mean ± S.D.	Variance	Mean ± S.D.	Variance
Open and coastal ocean								
In situ	0.20 ± 0.32	0.10	0.30 ± 0.51	0.29	0.24 ± 0.38	0.15	0.20 ± 0.26	0.07
CZCS	0.22 ± 0.55	0.30	0.24 ± 0.57	0.33	0.27 ± 0.64	0.42	0.28 ± 0.68	0.46
Blended	0.24 ± 0.55	0.31	0.32 ± 0.69	0.48	0.32 ± 0.68	0.46	0.30 ± 0.70	0.48
SeaWiFS	0.36 ± 0.90	0.82	0.38 ± 0.97	0.94	0.38 ± 1.08	1.15	0.38 ± 0.91	0.82
Open ocean								
In situ	0.17 ± 0.28	0.08	0.21 ± 0.32	0.10	0.20 ± 0.28	0.08	0.17 ± 0.20	0.04
CZCS	0.18 ± 0.42	0.18	0.18 ± 0.57	0.16	0.20 ± 0.64	0.18	0.21 ± 0.68	0.26
Blended	0.20 ± 0.44	0.19	0.25 ± 0.69	0.26	0.24 ± 0.68	0.20	0.24 ± 0.70	0.29
SeaWiFS	0.25 ± 0.31	0.10	0.26 ± 0.36	0.13	0.26 ± 0.34	0.12	0.26 ± 0.28	0.08
Coastal ocean								
In situ	0.55 ± 0.54	0.29	1.28 ± 1.34	1.81	0.75 ± 0.81	0.65	0.65 ± 0.53	0.28
CZCS	1.20 ± 1.39	1.93	1.33 ± 1.53	2.33	1.45 ± 1.70	2.88	1.60 ± 1.68	2.84
Blended	1.14 ± 1.39	1.94	1.54 ± 1.74	3.03	1.46 ± 1.78	3.17	1.50 ± 1.73	2.98
SeaWiFS	2.02 ± 3.12	9.71	2.20 ± 3.27	10.70	2.20 ± 3.77	14.20	2.11 ± 3.08	9.49

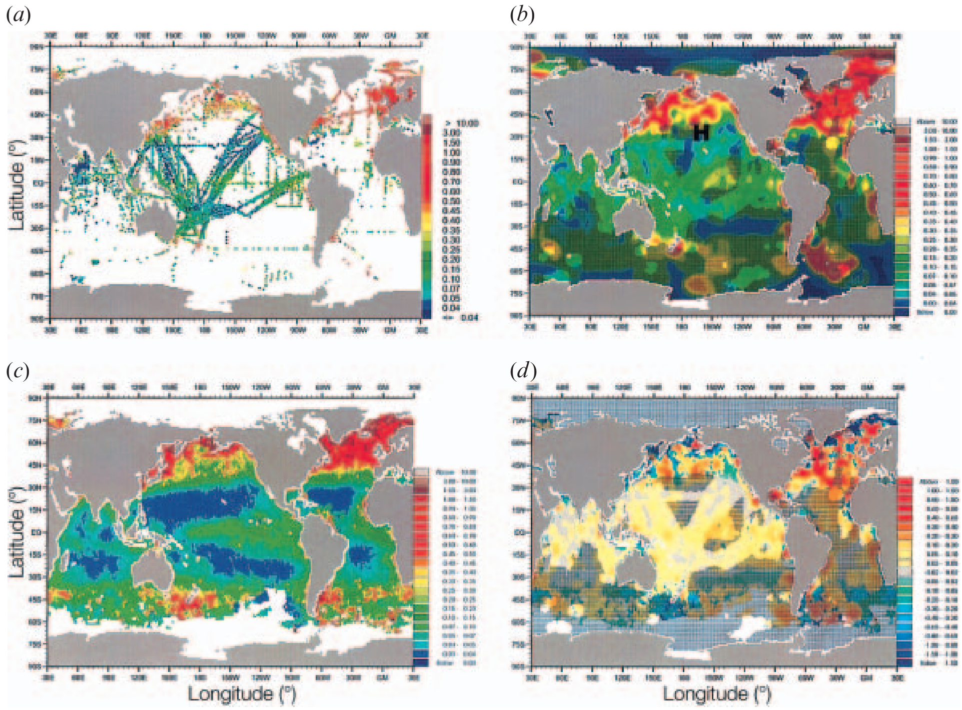

Figure 2. Spring (April–June) climatologies for *in situ* and CZCS data; (a) shows the distribution of *in situ* chlorophyll observations by 1×1 degree longitude-latitude squares. The colour dots represent the concentration of chlorophyll. (b) *In situ* climatology, H: represents the location of the Hawaii ocean time series (HOT); (c) CZCS climatology; (d) difference between spring (April–June) *in situ* and CZCS Climatologies. The units for chlorophyll are mg m^{-3}.

3.2. *Comparison of regional mean chlorophyll distributions*

The differences observed in the global means among these climatologies can be explored further by examining the major ocean basins (figure 4 and table 3). The pattern of highest SeaWiFS means is observed for most regions and seasons. There are some exceptions, *in situ* values are higher than SeaWiFS in the North Atlantic gyres for all seasons but summer (July–September). *In situ* values are also higher in the South Atlantic during spring (April–June). CZCS chlorophyll is lower, when compared to the other datasets, in the North Atlantic gyre, Equatorial Pacific and South Pacific and Equatorial Indian oceans, for all seasons. CZCS chlorophyll is also lowest in the North Pacific gyre for all but the fall season (October–December).

The four datasets have similar patterns of seasonal highs and lows in the North Central Pacific gyre, North Indian and Southern Ocean. Agreement is also found in the seasonal highs for the Equatorial Indian and Pacific Oceans, and seasonal lows in the Subarctic North Pacific, North Atlantic gyre and South Indian Ocean. The winter chlorophyll minima is located in the equatorial Indian for *in situ* and the blended dataset and in the South Pacific for CZCS and SeaWiFS. During spring, the equatorial Indian Ocean shows the lowest chlorophyll using the *in situ*, blended and CZCS data (the South Pacific is shown as the basin with the lowest summer chlorophyll with SeaWiFS). During summer, the North Pacific gyre has the lowest

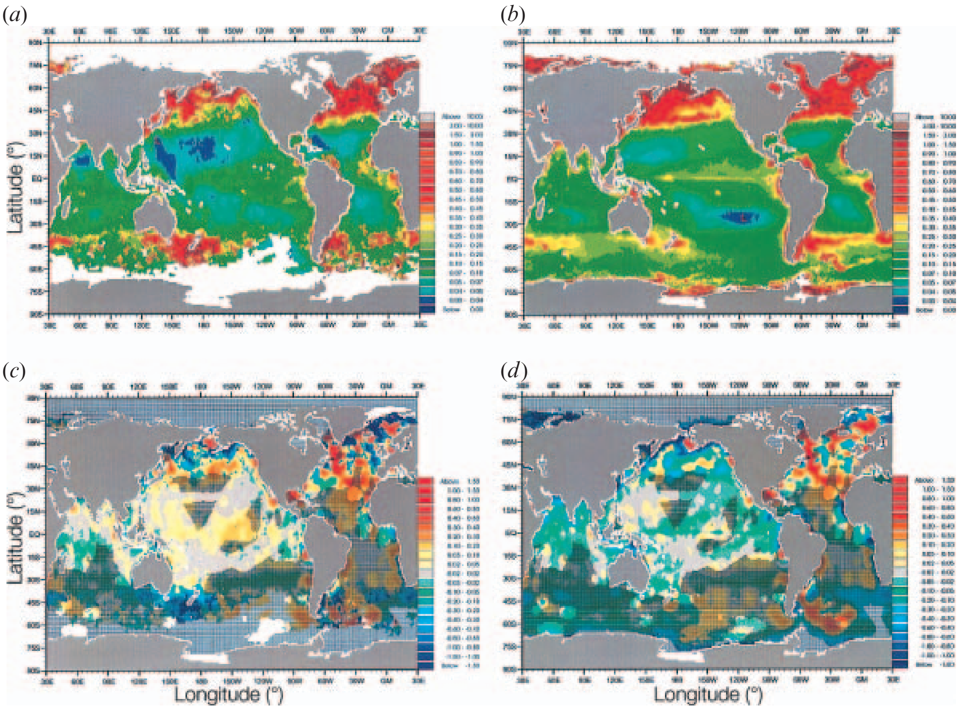

Figure 3. Spring (April–June) climatologies for blended *in situ*/CZCS (a) and SeaWiFS (b) data; (c) shows differences between *in situ* and Blended; and (d) difference between *in situ* and SeaWiFS climatologies. The units for chlorophyll are mg m^{-3}.

values for *in situ*, CZCS and blended chlorophyll, SeaWiFS shows a minima in the South Pacific. The fall minima is in the South Pacific for all datasets.

The one-degree square seasonal mean from each dataset were compared to seasonal chlorophyll means computed from 10 years of data at HOT (Kleypas and Doney 2001). The spring (April–June) chlorophyll mean at HOT is 0.067 mg m^{-3}. The *in situ* climatological mean at the same location is 0.07, CZCS is 0.04, blended 0.05 and SeaWiFS 0.09 mg m^{-3}.

4. Discussion

Global chlorophyll distributions follow a pattern of highest concentrations at high latitudes, and lowest in the mid-ocean gyres. The Northern and Southern Hemisphere gyres are separated by moderate chlorophyll concentrations at the equator. All data show that the Northern Hemisphere typically has higher chlorophyll concentrations than the Southern Hemisphere for all seasons. The highest chlorophyll concentrations are found in the subarctic North Pacific and North Atlantic. Chlorophyll concentrations tends to be twice as high in the Atlantic compared to the Pacific high latitudes, except for SeaWiFS, for which they are about equal. The Atlantic Ocean, at all latitudes, generally has higher chlorophyll concentrations than the Pacific and Indian Oceans with the exception of the North Indian Ocean which has a different seasonal pattern of circulation than the gyres located at the same latitude in the Pacific and Atlantic Oceans. The lowest chlorophyll concentrations are observed in either the North Pacific gyre, Equatorial Indian or

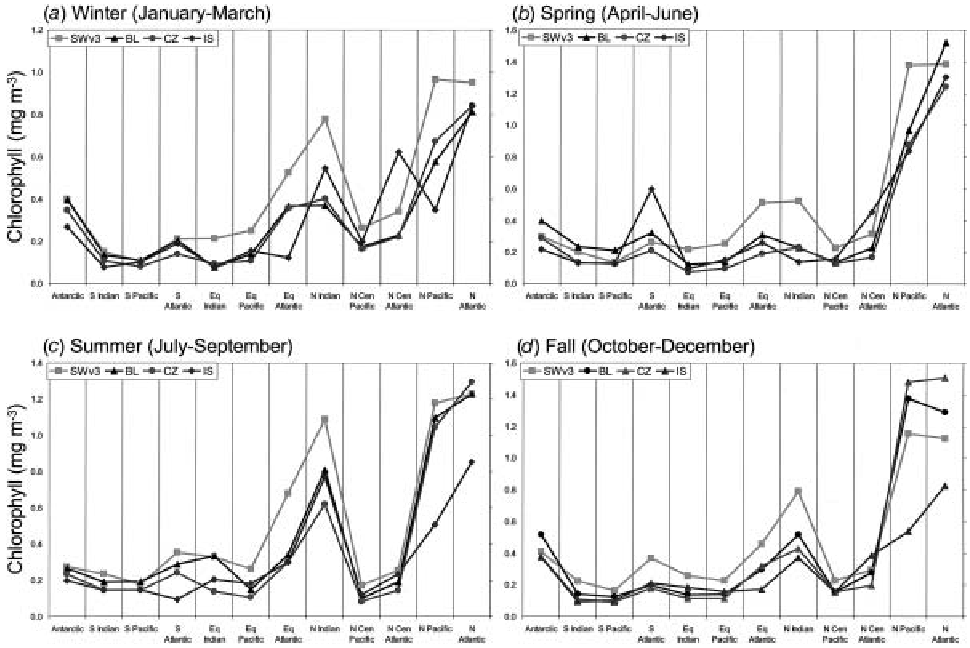

Figure 4. Regional means for *in situ* (IS), CZCS (CZ), blended analysis (BL) and SeaWiFS (SW) chlorophyll; (a) Winter (January–March), (b) Spring (April–June), (c) Summer (July–September), (d) Fall (October–December). The connecting lines across basins are meant only to show the seasonal and spatial variability in chlorophyll among these datasets.

South Pacific Oceans. The four chlorophyll climatologies investigated here all follow these general patterns. This suggests that all of the climatologies capture the large scale spatial distributions of global chlorophyll concentrations.

The magnitudes of chlorophyll determined by these climatologies can be quite different on global and basin scales. It is possible that some of these differences are natural and reflect the differences in the time period for which the climatologies were constructed. The *in situ* climatology is based on data from the 1950s to the late 1990s, CZCS and blended span from 1978–1986 (the length of the CZCS record) and SeaWiFS spans from fall 1997 to spring 2001 (time periods are shown in table 4). Chlorophyll distributions in most ocean basins, show not only a strong seasonal signal (i.e. studies by Yoder *et al.* 1993, Banse and English 1994), but also year-to-year differences (i.e. Venrick *et al.* 1987, Falkowski and Wilson 1992, Halpern and Feldman 1994, Thomas *et al.* 1994, Gregg and Conkright 2001). For instance, inter-annual variability due to El Niño and La Niña can produce significantly different results. During a strong El Niño, deepening of the thermocline results in upwelling of nutrient-depleted waters leading to a decrease in chlorophyll concentrations, from $0.2\,\mathrm{mg\,m^{-3}}$ to less than $0.05\,\mathrm{mg\,m^{-3}}$ (Chavez *et al.* 1999). During La Niña episodes, the thermocline shoals, and high nutrient concentrations are entrained in the surface waters resulting in chlorophyll concentrations of $>0.2\,\mathrm{mg\,m^{-3}}$ (Chavez *et al.* 1999). SeaWiFS was launched during the strong 1997–1998 El Niño event, followed by a La Niña event. High chlorophyll from SeaWiFS for the tropical Pacific and Indian Oceans may indicate that the signal from La Niña dominates this regional 'climatology'. The CZCS era saw an El Niño during 1982–1983 and two weak La Niñas during fall 1983 to spring 1984 and during fall 1984 to spring 1985.

However, a more likely possibility is that these differences among the climatologies are the result of biases in the dataset methodologies or analysis. Each datasets has its own set of biases, which can be linked to the discrepancies observed between these datasets.

4.1. *Biases associated with the in situ chlorophyll climatology*

The *in situ* dataset produced the lowest global and regional chlorophyll estimates of the four climatologies. The *in situ* dataset also had the lowest global variance of the datasets, up to 8 times less than the CZCS data, which had the next lowest variance (figure 1(b)). Biases may be introduced into the analysis of historical data due to differences in measurement techniques used over time, lack of representative spatial and temporal coverage of data, and the choice of analysis. Measurement errors can occur during sampling, filtration, storage, lack of calibration of the fluorometer and problems associated with the accuracy of the fluorometric techniques (Dandonneau 1982, Clemons and Miller 1984, Trees *et al.* 1985, Balch *et al.* 1992). For instance, the choice of filters, glass fibre (GF/C) or nucleopore (GF/F) can lead to an underestimate of chlorophyll (Dickson and Wheeler 1993, Herbland *et al.* 1985) especially in oligotrophic waters where picoplankton dominate (Phinney and Yentsch 1985).

The primary problem with this *in situ* climatology is data sparseness. The percentage of possible one-degree grid locations occupied by in situ points ranges from 0.0% in the South Atlantic summer to 43% in the equatorial Pacific fall (table 1). At this level of sparseness, the *in situ* climatology may be unrepresentative in some regions. The overall low values produced by the objective analysis may be a result of extrapolating from a few observations over a large area. For instance, the few observations in the Southern Hemisphere (table 1) would be extrapolated to represent the mean chlorophyll for the entire region, resulting in low variability (as shown with the low variances) and low basin means. Further evidence of this underestimate is that the blended analysis, which used unanalysed *in situ* chlorophyll and extrapolates according to the spatial distribution provided by the CZCS fields, led to overall increased chlorophyll concentrations (Gregg and Conkright 2001). For these reasons, we conclude that the generally low global and regional values produced by the *in situ* dataset are systematic underestimates of the actual chlorophyll.

4.2. *Biases associated with the CZCS chlorophyll climatology*

The CZCS typically produces the second lowest chlorophyll estimates. Its global variances are also second lowest. Biases associated with the CZCS archive are dominated by poor sampling and methodological inadequacies. The CZCS was a limited time/space sensor, i.e. it did not operate continuously or uniformly over all ocean basins. The CZCS provided wide area and repeat sampling of chlorophyll never observed before, but the lack of random sampling restricted its representativeness. There was a definite bias toward greater coverage in the Northern Hemisphere compared to the Southern Hemisphere, and within the Northern Hemisphere, toward the North Atlantic Ocean where about 30% of the data were collected (McClain *et al.* 1990).

Methodology problems, calibration of the sensor and atmospheric correction, especially the choice of a constant aerosol type (marine), are the main source of bias

Table 3. Regional chlorophyll mean values (mg m^{-3}) for *in situ* (IS), CZCS (CZ), Blended Analysis (BL) and SeaWiFS (SW) climatologies.

	Subarctic North Atlantic				Subarctic North Pacific				Southern Ocean			
Season	IS	CZ	BL	SW	IS	CZ	BL	SW	IS	CZ	BL	SW
Winter	0.84	0.84	0.81	0.95	0.35	0.67	0.58	0.97	0.27	0.35	0.40	0.40
Spring	1.30	1.24	1.52	1.39	0.84	0.88	0.97	1.38	0.22	0.29	0.40	0.30
Summer	0.85	1.30	1.23	1.23	0.51	1.05	1.10	1.18	0.20	0.23	0.26	0.27
Fall	0.83	1.51	1.29	1.13	0.54	1.48	1.38	1.16	0.38	0.38	0.52	0.41
	North Central Atlantic				North Central Pacific				North Indian			
Season	IS	CZ	BL	SW	IS	CZ	BL	SW	IS	CZ	BL	SW
Winter	0.62	0.22	0.23	0.34	0.20	0.17	0.18	0.27	0.55	0.40	0.37	0.78
Spring	0.45	0.17	0.23	0.32	0.16	0.13	0.14	0.23	0.14	0.23	0.23	0.53
Summer	0.23	0.14	0.19	0.25	0.12	0.08	0.10	0.17	0.77	0.62	0.81	1.09
Fall	0.39	0.20	0.28	0.29	0.15	0.16	0.16	0.23	0.37	0.43	0.52	0.79

Table 3. (*Continued*).

Season	Equatorial Atlantic				Equatorial Pacific				Equatorial Indian			
	IS	CZ	BL	SW	IS	CZ	BL	SW	IS	CZ	BL	SW
Winter	0.12	0.36	0.37	0.53	0.16	0.11	0.14	0.25	0.08	0.09	0.08	0.22
Spring	0.26	0.19	0.31	0.52	0.15	0.10	0.14	0.25	0.10	0.08	0.12	0.22
Summer	0.30	0.30	0.34	0.68	0.18	0.11	0.15	0.26	0.20	0.14	0.34	0.33
Fall	0.17	0.32	0.30	0.46	0.16	0.11	0.14	0.23	0.19	0.12	0.14	0.26

Season	South Atlantic				South Pacific				South Indian			
	IS	CZ	BL	SW	IS	CZ	BL	SW	IS	CZ	BL	SW
Winter	0.19	0.14	0.20	0.21	0.10	0.08	0.11	0.11	0.08	0.11	0.14	0.15
Spring	0.60	0.21	0.32	0.27	0.13	0.12	0.21	0.14	0.13	0.14	0.24	0.20
Summer	0.10	0.24	0.29	0.36	0.15	0.15	0.19	0.18	0.15	0.15	0.19	0.24
Fall	0.21	0.18	0.20	0.37	0.10	0.09	0.13	0.16	0.10	0.11	0.14	0.22

Table 4. Years represented by each chlorophyll climatology.

Season	*In situ*	CZCS	Blended	SeaWiFS
Winter (January–March)	1957–1998	1980–1986	1980–1986	1998–2001
Spring (April–June)	1957–1998	1980–1986	1980–1986	1998–2001
Summer (July–September)	1958–1998	1980–1986	1980–1986	1998–2000
Fall (October–December)	1955–1998	1979–1985	1979–1985	1997–2000

with CZCS data. These problems led to an underestimation of the prevailing chlorophyll concentrations. A reanalysis of the calibration (Evans and Gordon 1994) produced a reduction in the water-leaving radiance at 443 nm, which is inversely related to chlorophyll. The constant marine aerosol chosen for atmospheric correction, although generally representative in the open oceans, has different spectral properties from other aerosol types, such as those of continental origin. By limiting the aerosol type to marine, insufficient aerosol radiance at 443 nm was attributed when other aerosol types were present, thus resulting in an underestimate of chlorophyll. In addition, some observers have suggested that cloud cover obscured CZCS sampling during periods of high phytoplankton growth leading to seasonal underestimates of the chlorophyll concentrations (Mitchell *et al.*1990, Müller-Karger *et al.* 1990) though English *et al.* (1996) found an overestimate in the vicinity of Ocean Weather Station Papa. Phytoplankton species distributions, with different light scattering properties can also result in under or overestimates in satellite chlorophyll (Balch *et al.* 1989, Brown and Yoder 1994). However, numerous studies, comparing ship and CZCS chlorophyll show, in general, an underestimate of CZCS compared to ship observations globally (Balch *et al.* 1992), in the Southern Ocean (Mitchell and Holm-Hansen 1991, Sullivan *et al.* 1993, Arrigo *et al.* 1994), the tropical Atlantic (Monger *et al.* 1997), the Bering Sea (Müller-Karger *et al.*1990), Barents Sea (Mitchell *et al.* 1991), Peruvian current (Chavez 1995), Gulf of Mexico (Biggs and Müller-Karger 1994), among others. CZCS chlorophyll matches shipboard observations in such places as the Ross Sea (Arrigo *et al.* 1998) and coastal California (Chavez 1995).

Further evidence of bias is obtained by analysing the results of the blended analysis, where *in situ* data are inserted into the analysed field as interior boundary conditions and the CZCS field is adjusted to conform to these values. In effect, the CZCS is used as an interpolation/extrapolation function among the *in situ* points, which serve a bias correction function (Reynolds 1988). In this analysis, when interannual mismatches between *in situ* and satellite sensor data were accounted for, the net effect was to elevate the CZCS fields (Gregg and Conkright 2001). These results suggest that the CZCS record is an underestimate of the actual chlorophyll climatology.

4.3. *Biases associated with the blended chlorophyll climatology*

The blended dataset produces chlorophyll estimates that are typically intermediate between the CZCS and SeaWiFS climatologies. Blending of CZCS and *in situ* data were performed in an attempt to improve on the existing seasonal chlorophyll climatologies (Gregg and Conkright 2001). The blended analysis uses the high quality, but spatially limited, *in situ* observations to modify the high coverage satellite sensor data. The accuracy of the blended chlorophyll analysis is constrained by the sparseness and quality of the *in situ* data and therefore the extent to which it can adjust for the biases in the satellite sensor data. In the absence of *in situ* data, the blended dataset reverts to the CZCS, and thus adopts all of the biases of the CZCS. These circumstances are typical in the central South Atlantic ocean and sometimes the North Atlantic in the blended dataset. However, given the bias correction nature of the method using the unanalysed *in situ* data, it is likely that it provides a more representative climatology except in the situations of extreme data sparseness.

4.4. *Biases associated with the SeaWiFS chlorophyll climatology*

The SeaWiFS mission was conceived to improve on its predecessor, CZCS. SeaWiFS has new bands enabling a better characterization of aerosols (Gregg *et al.* 1997), better signal-to-noise ratios (Gordon, 1997), an extensive calibration/validation program (McClain *et al.* 1998), solar and lunar stability monitoring capabilities (Barnes *et al.* 1999), comprehensive atmospheric correction algorithms (Gordon and Wang 1994) and possibly most important, a dedicated routine global observational duty cycle.

SeaWiFS chlorophyll concentrations nearly always represent the highest estimates among the four climatologies. SeaWiFS global chlorophyll is 32–93% larger than *in situ* estimates. These trends hold for nearly every region and season (figure 4). SeaWiFS variances are also much larger than any of the other datasets (figure 1(b)). Thus the SeaWiFS chlorophyll estimates are both larger and more variable than observed by any other method.

It is difficult to assess whether these results indicate a bias in the SeaWiFS dataset. A possible explanation for the SeaWiFS results in the Pacific Ocean is that the first two years of SeaWiFS data have been in anomalous conditions–El Niño from near launch to May 1998, followed by a La Niña which lasted until September 2000. These events tend to depress (El Niño) and increase (La Niña) chlorophyll concentrations in the tropical Pacific. Two years of La Niña balanced against one year of El Niño and a partial 'normal' year (late 2000) can produce higher mean values in the tropical Pacific than normal. Similar effects can occur in the Indian Ocean, which also showed significant El Niño effects in 1997–1998 (Murtugudde *et al.* 1999). However, these effects are predominantly restricted to the tropical Pacific and Indian Oceans. Although comparisons between ship and SeaWiFS chlorophyll are few, initial results for the Southern Ocean show that SeaWiFS chlorophyll are higher than CZCS (Moore and Abbott 2000) but still underestimate chlorophyll when compared to *in situ* observations (Dierssen and Smith 2000, Moore *et al.* 1999b). Overestimates of SeaWiFS chlorophyll compared to *in situ* chlorophyll were also observed in the shelf waters of Northern Chile during the 1997–1998 El Niño (Thomas *et al.* 2001).

Another explanation is that global and regional SeaWiFS mean values are adversely impacted by high coastal values. When coastal values (defined as $\leqslant 200$ m in depth) are removed, SeaWiFS global mean estimates decrease dramatically (figure 5(a) and table 2). SeaWiFS chlorophyll still exceeds the other climatologies but the discrepancies are much smaller. Variances for SeaWiFS, in non-coastal areas (shown in table 2), range from 0.5–1.5 larger than *in situ* variances, but 2–3 times lower than CZCS and blended variances. In coastal regions, SeaWiFS chlorophyll is three times higher than *in situ* chlorophyll for all seasons except spring, and almost twice as high than CZCS and blended for all seasons (figure 5(b)). These high values affect the global and regional means and also produce the very large variances observed in the SeaWiFS record.

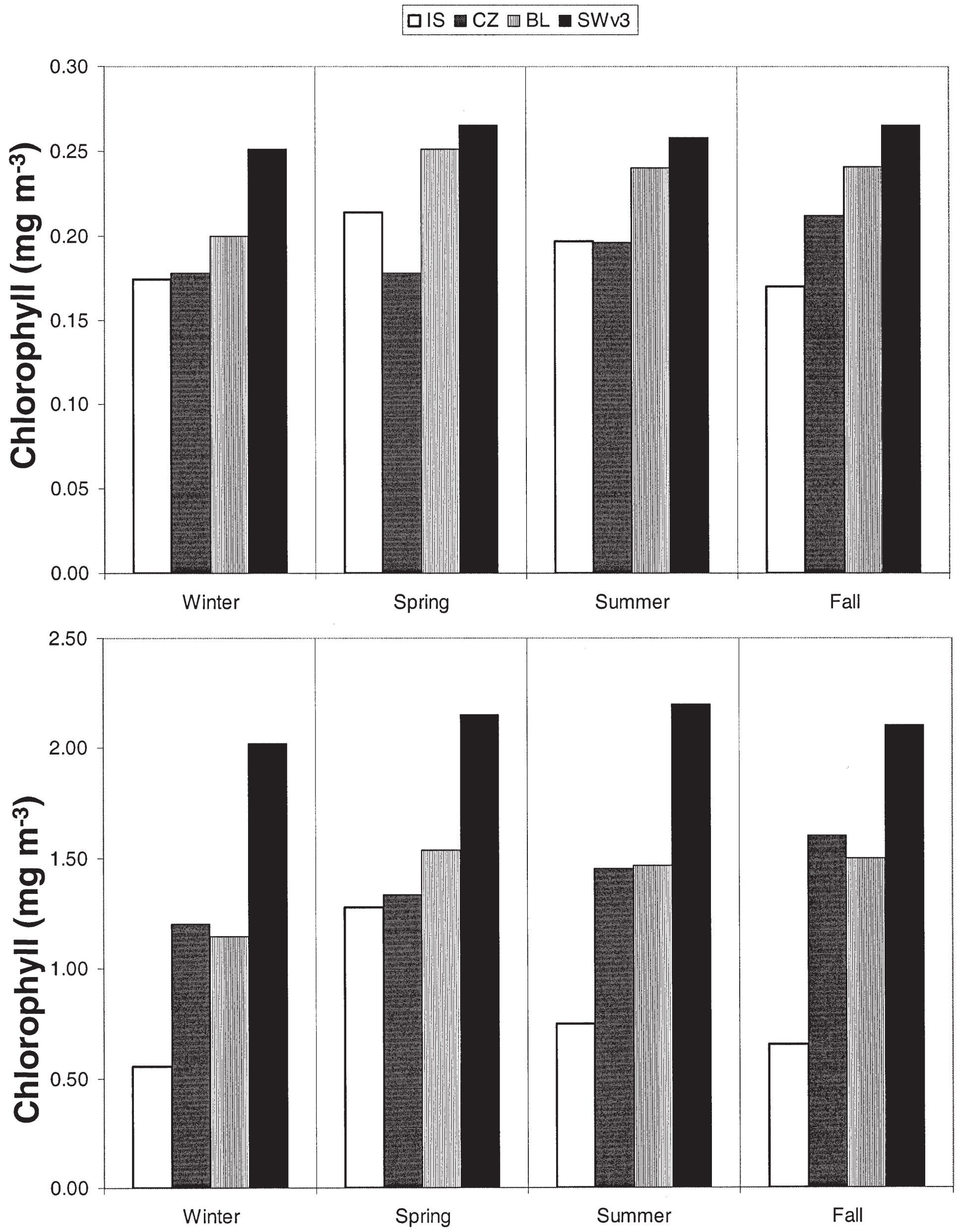

Figure 5. Global chlorophyll estimates (mg m^{-3}), for the open ocean only, by season for *in situ*, CZCS, blended analysis and SeaWiFS data shown in top panel, for the coastal ocean in the bottom panel.

In order to further examine the SeaWiFS results, we compare the chlorophyll mean estimates derived from SeaWiFS Version 2 (SWv2) and SeaWiFS Version 3 (SWv3) for the same time period (fall 1997–summer 1999). Mean chlorophyll and variances for the global ocean, open ocean and coastal ocean are shown in figure 6. Global chlorophyll means for SWv3 are lower by 9–17% than SWv2, for all seasons.

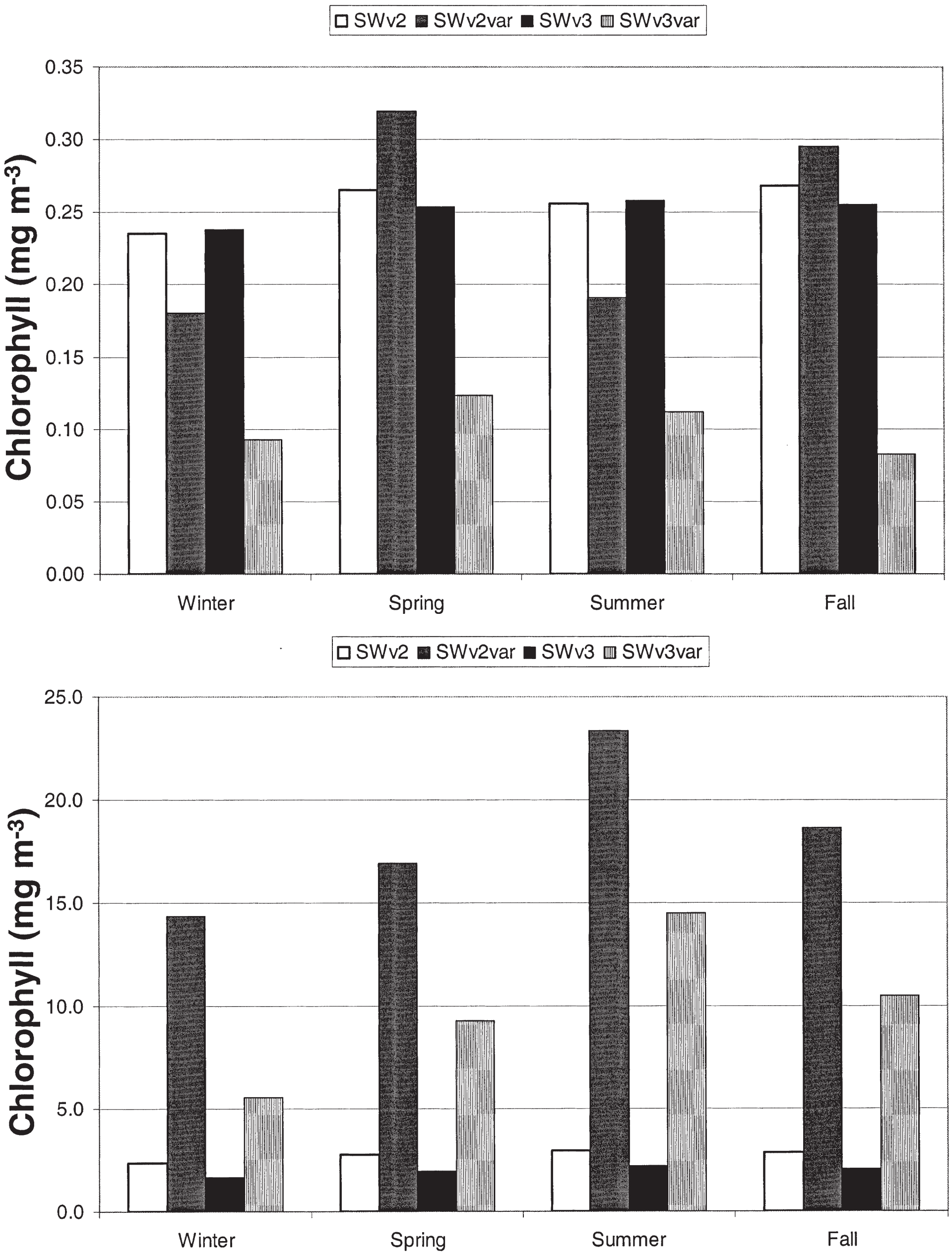

Figure 6. Comparison of global SeaWiFS Version 2 and SeaWiFS Version 3 mean chlorophyll and variances for the same time periods (Fall 1997–Summer 1999). White bars indicate SeaWiFS Version 2 chlorophyll (SWv2), hatched bars show the variances (SWv2var), black bars are for SeaWiFS Version 3 chlorophyll (SWv3), and square bars are the variances (SWv3var). The top panel are the results for the open ocean, and the bottom panel for the coastal ocean.

The largest differences are observed in the variances, which are 74%–135% lower in SWv3 as compared to SWv2. SWv2 also shows higher chlorophyll in the mid ocean gyres when compared to the other climatologies.

The main effect of the reprocessing effort appears to be application of the Siegel *et al.* (2000) method to include effects of scattering of light by phytoplankton at large concentrations in the near-infrared wavelengths (765 nm and 865 nm), and replacement of the ocean chlorophyll 2 bio-optical algorithm (OC2; O'Reilly *et al.* 1998) with the OC4 algorithm. The Siegel *et al.* (2000) correction is mostly responsible for the reduction of global means and variances, by vastly reducing the number of excessively high chlorophyll values found in SWv2. The OC4 bio-optical algorithm is mostly responsible for reducing mean chlorophyll values in the gyres, by utilizing 443 nm rather than 490 nm in these regions, and thus increasing the sensitivity of the algorithm at these low chlorophyll concentrations.

Based on these results we believe we can reach tentative conclusions on the quality of the SeaWiFS data. First, we believe that SeaWiFS chlorophyll data in the open ocean are valid. Global mean values are $<10\%$ higher than the blended climatology, except in winter when it is 20%. Considering that the effect of the blended analysis on the CZCS was to generally elevate the global means, and that there were large regions of sparse *in situ* sampling, we expect that improved sampling would have the net effect of raising the blended means even more. Thus any differences between SeaWiFS and the blended climatology would likely be the result of interannual variability. Second, the low variances in the global ocean exhibited by SeaWiFS are the result of the NIR correction of Siegel *et al.* (2000). If this correction were applied to the CZCS (and hence included in the blended data), we would expect a similar reduction of variances producing results similar to SeaWiFS. Minor residual differences, if they exist, could be artifacts of sensor noise or processing/algorithm differences between the datasets.

On the coasts, the high SeaWiFS values are more difficult to explain. There is major reduction of global mean chlorophyll in Version 3 from Version 2, suggesting improvement, but the means and variances are still very different from the other climatologies. SeaWiFS values could be representative, since the regular frequency of coverage by SeaWiFS would enable it to capture sporadic effects that produce ephemeral blooms or recessions of chlorophyll. These events would contribute to higher means and variances. However, despite improvements in the reprocessing, coastal data continue to be plagued with low radiances, often associated with what appear to be absorbing aerosols, which are not identified in the algorithms. In the extreme case, the result is derived water-leaving radiances that are negative, but less extreme cases will produce erroneously high chlorophyll retrievals. As researchers utilize and evaluate the products from the third reprocessing of SeaWiFS, we will be able to determine whether the higher chlorophyll values observed are real, or a result of continuing problems with the algorithm or with the sensor. However, given our experience with blending CZCS data and the nature of the problems encountered by SeaWiFS, we believe that the blended analysis can be a powerful tool to improve SeaWiFS chlorophyll data, particularly on the coasts where the problems are most severe and where *in situ* sampling frequency is greatest.

4.5. *Implications to the global carbon cycle*

Over the past two decades, there has been an increased awareness of the importance of the world ocean as part of the Earth's climate system. Large scale patterns of ocean productivity and global distributions of biological parameters pertinent to the ocean carbon system, are critical in understanding the impact of the oceans on our climate. One of the controlling processes of the CO_2 content in surface waters is the CO_2 drawn down in the spring and summer by phytoplankton, and regenerated in the winter (Broecker and Peng, 1982). Recent models use chlorophyll data from ocean colour satellites to calculate primary production estimates for the global ocean (Longhurst *et al.* 1995, Antoine and Morel 1996, Behrenfeld and Falkowski 1997, Iverson *et al.* 2000). However, as we have shown in the previous discussion, there are biases inherent in each chlorophyll dataset available which will produce different results in studies such as the estimation of carbon budgets, carbon pathways and primary production. These various estimates can have a large impact when trying to assess the magnitude of the oceanic carbon sink.

5. Conclusions

Currently, three sources of data are available for understanding the large scale seasonal distributions of chlorophyll in the surface ocean: historical *in situ* data (1955–1998), CZCS (1978–1986) and SeaWiFS (1997–2001). Additionally, blended CZCS and *in situ* data were compared. A comparison of chlorophyll distributions using these climatologies show that general seasonal and spatial patterns are in agreement: (1) high chlorophyll at high latitudes and coasts, low chlorophyll in mid-ocean gyres; (2) higher chlorophyll in the Northern Hemisphere compared to the Southern Hemisphere; and (3) higher chlorophyll in the Atlantic than in the Pacific Ocean. Major disagreements are observed in the magnitudes of chlorophyll concentrations for different regions and seasons. For most regions and seasons, SeaWiFS chlorophyll is highest, *in situ* chlorophyll is lowest; blended chlorophyll is intermediate between CZCS and SeaWiFS.

We are left with the question of which dataset best represents the surface distribution of chlorophyll. *In situ* and CZCS appear to underestimate chlorophyll as shown by the results of the blended analysis which increases the global and regional means. *In situ* data are limited by poor spatial resolution, and the method used to extrapolate into unsampled areas, appears to bias the analysis toward low values. CZCS data are impacted by calibration and algorithm problems which leads to an underestimate. Blended CZCS/*in situ* and SeaWiFS data appear to be reasonable representations of climatological global chlorophyll in the open ocean. Differences between these last two climatologies are $<10\%$ in every season except winter, when SeaWiFS was higher by 25%. Although SeaWiFS chlorophyll is always higher than the other datasets in the open ocean, the relatively small differences could be due to natural variability. SeaWiFS may overestimate coastal chlorophyll, with values 30%–77% higher than the next closest climatology. Blending of *in situ* and satellite sensor data, originally applied to correct biases in the satellite sensor data, may produce the best climatology. This method takes advantage of the higher quality of *in situ* data, and the spatial variability of satellite sensor data. It is only hindered by the sparseness of *in situ* chlorophyll data, and by the quality of satellite sensor data where no *in situ* observations are available. In the case of extreme *in situ* data sparseness, the blended set reverts to the satellite fields and thus acquires all of the biases associated with the satellite sensor data. The blended method may be of greatest use for SeaWiFS in coastal areas, where the algorithm problems are greatest and the *in situ* sampling frequency is also greatest.

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