Global Seasonal Climatologies of Ocean Chlorophyll:
Blending *In situ* and Satellite Data for the CZCS Era

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Submitted to Journal of Geophysical Research – Oceans, 1999

Abstract. The historical archives of *in situ* (National Oceanographic Data Center) and satellite (Coastal Zone Color Scanner) chlorophyll data were combined using the blended analysis method of Reynolds [1988] in an attempt to construct an improved climatological seasonal representation of global chlorophyll distributions. The results of the blended analysis differed dramatically from the CZCS representation: global chlorophyll estimates increased 8-35% in the blended analysis depending upon season. Regional differences were even larger, up to 140% in the equatorial Indian Ocean in summer (during the southwest monsoon). Tropical Pacific chlorophyll values increased 25-41%. The results suggested that the CZCS generally underestimates chlorophyll. Regional and seasonal differences in the blended analysis were sufficiently large as to produce a different representation of global chlorophyll distributions than otherwise inferred from CZCS data alone. Analyses of primary production and biogeochemical cycles may be substantially impacted by these results.

1. Introduction

Satellite observations of ocean color provide large-scale, repeat coverage sampling of global ocean chlorophyll that are necessary to help understand the role of phytoplankton on biogeochemical cycling, climate change, and fisheries. However, remotely-sensed data are subject to several sources of error that affect their accuracy, for example, calibration, atmospheric correction algorithm errors, uncertainties in knowledge of the atmospheric optical state, and problems deriving chlorophyll from radiances. Conventional *in situ* methods (e.g., ships and buoys) typically provide high quality, accurate data, but can only produce extremely limited spatial observations due to the expense of sea operations and the large areal extent of the ocean. Thus, *in situ* data provide high quality chlorophyll information that satellites cannot, and satellites provide horizontal and temporal observations that *in situ* methods cannot. A blending of data sources can maximize the strengths of each data set and produce a high quality, large spatial, data set of ocean chlorophyll.

In this paper we combine *in situ* chlorophyll data from the extensive archive (~130,000 profiles) maintained by the NOAA/National Oceanographic Data Center (NODC) with remotely-sensed data from the Coastal Zone Color Scanner (CZCS) in an attempt to provide an enhanced set of seasonal climatologies. We utilize the Conditional Relaxation Analysis Method [*Oort*, 1983] that has been successfully applied to sea surface temperature (SST) data [*Reynolds*, 1988]. The advantage of this method is that it preserves the integrity of the *in situ* values while preventing the overwhelming of *in situ* data with the vastly larger number of observations by satellites, at the same time taking advantage of the spatial variability observed from the satellite.

We limit the analysis to the CZCS era (1978-1986) because of the availability of large amounts of *in situ* data and satellite data. The CZCS record represents the only multi-year satellite ocean color data set currently available to produce seasonal climatologies. Global primary production models [*Iverson et al.*, 1999; *Behrenfield and Falkowski*, 1997; *Antoine et al.*, 1996] utilize climatological CZCS pigment data as a primary independent variable. Chlorophyll scales linearly and sometimes even non-linearly in these models, so it is important to provide enhanced estimates of global ocean chlorophyll in order to improve estimates of global primary production.

2. Methods

which the CZCS was operating, and then averaging the seasons over the CZCS years. This enables us to remove the known sampling alias occurring in CZCS seasonal composites [*Feldman et al.*, 1989] due to unequal sampling of months within seasons.

CZCS pigment estimates are converted to chlorophyll by

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

[*O'Reilly et al.*, 1998] where S indicates satellite-derived chlorophyll and P indicates satellite-derived pigment. 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].

3. Blended Analysis

In situ and satellite data are merged using the Conditional Relaxation Analysis Method (CRAM; [*Oort*, 1983]). This analysis assumes that *in situ* data are valid (after rigorous quality control), and uses these data directly in the final product. The satellite chlorophyll data are inserted into the final field using Poisson's equation

$$\nabla^2 C = \Psi \qquad (2)$$

where C is the final gridded field of chlorophyll, and Ψ is a forcing term, which is defined to be the Laplacian of the gridded satellite chlorophyll data ($\nabla^2 S$). *In situ* data serve as internal boundary conditions, and are inserted directly into the solution field C

$$C_{ibc} = I \qquad (3)$$

where the subscript $_{ibc}$ indicates internal boundary condition and I is the *in situ* value of chlorophyll. Thus *in situ* data appear un-adjusted in the final blended product. *In situ* data are averaged over 3 x 3 chlorophyll regions dominating the high latitudes and coastal regions are defined as Domain 3. The CZCS seasonal climatologies are first smoothed by averaging over 3 grid locations in longitude and latitude (i.e., a 3 x 3 grid point box comprising 9 total values). This reduces some of the variability within these domain characterizations, but additional tests are required to assure intra-domain coherence. The results exhibit a reasonable representation of high and low chlorophyll domains in the global ocean (Figure 2), where mid-ocean gyre domains of low pigment are clearly distinguished from higher concentrations encountered in the polar and sub-polar domains, and equatorial upwelling domains are apparent. Methods using the mean and variance to distinguish functional domains [*Esaias et al.*, 1999] produce similar results.

First the high chlorophyll and equatorial data are excluded (only data from Domain 1 are used), then the high chlorophyll domains are excluded from the analysis (only data from Domains 1 and 2 are used), and finally all data are blended regardless of regional definition (Figure 1). This produces three separately computed blended analysis products. The final blended chlorophyll analysis is produced by using the low chlorophyll blend in Domain 1 the equatorial blend in the tropics (Domain 2), and high chlorophyll data in Domain 3 (Figure 1). This method allows *in situ* values in high chlorophyll domains to affect other high chlorophyll regions in the final analysis, while preventing their influence into the low chlorophyll domains (e.g., the mid-ocean gyres), which is the main problem.

The effects of these methods are apparent in the sequence of blended analyses around the continental United States (Figure 3). When the blended analysis is performed using untransformed chlorophyll data with no domain restrictions, large coastal chlorophyll values on the Northeast US , climatology, we first evaluate *in situ*/satellite anomalies year-by-year in the seasonal data. These anomalies are averaged over the entire data record.

$$\log_{10}A(i) = \frac{\Sigma_y[\log_{10}I(i) - \log_{10}S(i)]}{n} \qquad (4)$$

where A represents the *in situ* - satellite anomaly at each grid point i, the summation is over years (y), and n is the number of years for which an anomaly is available (i.e., *in situ* and satellite data are coincident and co-located for a given year). Then *in situ* data are inserted into the seasonal climatology as anomalies from CZCS chlorophyll data.

$$\log_{10}C_{ibc}(i) = \log_{10}S(i) + \log_{10}A(i) \qquad (5)$$

Because of sparse satellite and in situ chlorophyll data when matching co-located and coincident points, we adjust non-coincident *in situ* values by the mean IAV-correction of nearby coincident values. We limit the proximity to 10° in longitude and latitude and exclude cross-regional values. The IAV correction can also ameliorate the effects of sensor degradation in the CZCS lifetime [e.g., *Evans and Gordon*, 1994].

In the analysis of the method, we define thirteen regions based on common geographical criteria, so that seasonal changes may be better evaluated. Boundaries of the geographical regions follow those used in the quality control of *in situ* data [*Conkright et al.*, 1994b, 1998]: Antarctic is defined as –50°, the North Pacific and Atlantic Oceans are northward of 40°, and equatorial regions are bounded by –10° and 10°.

often exceeding 20% and even >100% for the spring equatorial Atlantic and summer equatorial Indian Ocean. Negative anomalies (blended analysis < CZCS) are limited to the Northern Hemisphere and equatorial regions, and are usually smaller than the positive anomalies. Equatorial regions suggest large and persistent underestimation by the CZCS. For example, equatorial Pacific chlorophyll concentrations are typically 25-41% larger than CZCS estimates. 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, and the rms between *in situ* and CZCS is about 82% for each season.

3.3. Global Distributions of Chlorophyll in the Blended Analysis

Application of the blended analysis for the CZCS years shows that global scale patterns in chlorophyll are not substantially different from the CZCS (Figures 7-10). Seasonally, similar patterns of low chlorophyll concentrations in the mid-ocean gyres, high values in the high latitudes and coastal regions, and moderate values near the equator are apparent in both the CZCS data and the blended data sets. Considering that *in situ* values represent approximately 10% of the total data in the blended data sets, this suggests that the two data sets are in general agreement with respect to global spatial trends.

However, large regional and global differences between the blended analysis and CZCS estimates of chlorophyll are apparent at sub-region scales and are not evenly distributed. The global trend that the blended analysis produces generally larger estimates of chlorophyll than the CZCS holds, although there are exceptions. Some overall observations are 1) CZCS estimates of the eastern equatorial Pacific are consistently lower than *in situ* observations and the blended analysis in all

A similar small increase in the chlorophyll concentrations of the North Pacific gyre is apparent in the blended analysis, although there appears to be no change in the gyre size. A dramatic difference is the lower chlorophyll estimates in the blended analysis in the northeastern Pacific and Gulf of Alaska coupled with the increased estimates in the northwestern Pacific. There is good *in situ* sampling in the northeastern portion, but there are few northwestern observations contributing to the increase. Good sampling in the Japan and East China Seas lead to reductions of chlorophyll in the blended analysis, and suggest the CZCS may overestimate here.

3.3.2. Spring

Spring is the season of the largest change between the blended analysis and the CZCS estimates. Changes are widespread (Figure 8), with vast areas of the oceans exhibiting positive anomalies (blended chlorophyll > CZCS). The extensive North Atlantic spring bloom routinely observed in CZCS data is even more pronounced and larger in the blended analysis. All three tropical regions show large positive anomalies, as does the southeastern Indian Ocean and the entire oceanic region near Australia and New Zealand. The North and South Atlantic gyres have somewhat larger chlorophyll concentrations, and the North Atlantic gyre exhibits a substantial reduction in size. The northwestern Pacific has more *in situ* sampling in the spring than in the winter, and thus the positive anomaly here is better represented in the blended analysis. Poor *in situ* sampling in the Southern Hemisphere, coupled with discrepancies among the few samples, contributes to large anomalies. Some exceptions to the global positive anomaly trend are 1) extreme northwestern Pacific, Japan and Okhostk Seas, 2) northern Bering Sea, 3) northeastern Pacific, 4) Labrador Sea, 5) North Atlantic near Iceland, and 6) Mauritanian coast, which all exhibit negative anomalies.

In autumn there are some similar patterns in the anomalies with the other seasons, such as the negative anomalies in the northeast Pacific and Okhostk, Japan, and East China Seas, positive anomalies in the tropical Pacific, and most of the US East Coast. But there are some striking differences as well. The eastern Australian/New Zealand area for the first time is lower in the blended analysis than in the CZCS, as is the northern portion of the Patagonian shelf. These changes arise in the presence of substantial *in situ* observations. Heavy *in situ* sampling in the southern Indian Ocean and nearby Antarctic Ocean, as well as the Drake Passage and the Scotian Sea give rise to large positive anomalies between the two chlorophyll estimates. The south-central Pacific gyre is noticeably reduced in size and contains larger chlorophyll concentrations in the blended analysis, and the northern Pacific gyre exhibits more spatial variability. This is due to the expansion of the equatorial upwelling in the blended analysis. The North Atlantic is somewhat reduced in chlorophyll biomass in the blended analysis, primarily due to *in situ* observations in disagreement with the CZCS near Nova Scotia and in the Norwegian and North Seas. The Arabian Sea contains much larger chlorophyll concentrations in the blended analysis

4. Discussion

Application of the blended analysis of Reynolds [1988] to chlorophyll climatologies using the CZCS and the NODC global chlorophyll archive produces major differences in the representation of global and regional chlorophyll distributions and magnitudes from that estimated by the CZCS alone. Seasonally, the differences vary between 8 and 35% globally, and are always positive anomalies (blended > CZCS). This suggests that the CZCS underestimates global chlorophyll concentrations.

Most of the problems are eliminated by the log-transformation alone, as illustrated in Figure 3. However, the biomass domain restrictions are also important, in that they derive from the specific capabilities and deficiencies of remote ocean color sensors in general and the CZCS data set in particular. Calibration is one source of error that exhibits itself non-regionally, but it is only one of many issues for ocean color and the CZCS. Others include Case 2 waters [*Morel and Prieur*, 1977], improper characterization of the prevailing aerosol, high latitude errors associated with large solar zenith angles, and optically diverse phytoplankton compositions and associated detrital material that confound the bio-optical algorithms used to convert the satellite signal to chlorophyll. Many of these are in some way related to the biomass. For example, detrital material tends to be more prevalent in low chlorophyll concentrations [*Gordon et al.*, 1988]. Some of them, while not directly related to biomass, tend to occur coincident with biomass definitions, e.g., large solar zenith angles associated with large biomass polar regions, or continental aerosol types often located in high chlorophyll coastal areas. By separating functional domains, we attempt to construct an overall enhanced blended data set that accounts for satellite deficiencies while preventing the bias correction of the blended analysis from extending into domains in which different satellite biases are expected. The separation used here is most important for the open ocean gyres, since they are very sensitive to the blended analysis. Our method enforces the criterion that gyres must be sampled to be affected by blending. We prefer to tolerate lack of bias correction in the central gyres, which represent as close to ideal remote sensing conditions as exist for ocean color applications (co-varying detrital components, low and steady chlorophyll concentrations, marine aerosol predominance).

the presence of these aerosols produces an underestimate of chlorophyll. Monger *et al.* [1997] found this to be a significant contributor to CZCS underestimates observed in the tropical Atlantic.

Limited sampling by the CZCS can also produce a bias. If persistent cloud cover precludes sampling during times of phytoplankton growth and abundance, the seasonal estimates produced by the CZCS can be too small. Muller-Karger *et al.* [1990] and Mitchell *et al.* [1991] found this situation in the Bering and Barents Seas, respectively. Persistent cloud cover also impacts tropical regions, as a result of the Inter-Tropical Convergence Zone (ITCZ). Coupled with especially large losses due to the presence of sun glint, sampling aliases in these areas can be important and can produce a bias.

Case 2 waters, where optically-active suspended or dissolved materials are present and do not co-vary with chlorophyll, can produce different effects on the CZCS estimates of chlorophyll. Larger than normal CDOM concentrations clearly produce an overestimate of chlorophyll, since they absorb strongly at 443 nm and less so at 520 nm and 550 nm. However, smaller-than-normal amounts can produce the opposite effect. Upwelling areas may contain lower CDOM concentrations than expected by the CZCS bio-optical algorithms. Thomas *et al.* [1995] found one-third less DOM in the tropical Atlantic during the strong upwelling season than normal. Monger *et al.* [1997] attributed most of the CZCS underestimates they observed here to this effect. Suspended materials may have a more complex effect than CDOM. Since they scatter as well as absorb, they can produce an excessive water-leaving radiance signal at 670 nm, which the CZCS algorithms interpret as aerosol. More importantly, their effect on water-leaving radiance may be spectral, scattering more in the blue this is a region of very large spatial variability, where small mismatches in ship locations and satellite observations can be important. The phytoplankton species assemblages are quite different from those typically encountered in more temperate oceans, where the bio-optical algorithms were developed. Mitchell and Holm-Hansen [1991] developed regional bio-optical algorithms to account for the reduced optical efficiency of the large phytoplankton species, such as *Phaeocystis* spp. and diatoms that dominate here [*Arrigo et al.*, 1999]. The Antarctic Ocean is also subject to persistent cloud cover, which obscures sampling by satellite and may result in biases [*Muller-Karger et al.*, 1990; *Mitchell et al.*, 1991]. A noteworthy difference between the data estimates is the ribbon of high chlorophyll in the CZCS at the margin of the Antarctic coast, extending from about 30° E to the Ross Sea. This is greatly reduced by *in situ* observations and consequently the blended analysis, suggesting that it is ice mis-characterized as chlorophyll by the CZCS.

The southern Atlantic, Indian, and Pacific oceans all exhibit large positive anomalies in chlorophyll in the blended analysis relative to the CZCS data. This is true for all seasons. *In situ* sampling of the South Atlantic is very poor in every season but winter. However, the South Indian and South Pacific are sampled relatively well, except the South Indian Ocean in summer. *In situ* sampling sparseness must be considered when attempting to assess the performance of the blended analysis in these regions. Because of our method of constraints, the South Atlantic gyre tends not to be affected by the blended analysis, and most of the anomaly shown for the South Atlantic geographical region is driven by changes in the sub-arctic transition zone between 30° and 50° S. Recent studies have suggested a predominance of coccolithophores in this region in some seasons [*Eynaud et al.*, 1999]. These organisms can confound the remote sensing signal, by scattering light at 550 nm and 670 nm reported in the tropical Atlantic during the strongest upwelling season [*Thomas et al.*, 1995]. Analysis of cloud cover and cloud optical thickness from the International Satellite Cloud Climatology Project (ISCCP) indicate that this area is impacted by large and persistent cloud cover, especially in the spring and summer. This cloud cover is related to the ITCZ, and produces monthly mean values of 80% cloud fraction at times, and optical thickness exceeding 8, especially in spring and summer. Sun glint is an additional impediment to CZCS observations in this region. Although the CZCS tilted to avoid sun glint, often the tilt was not operated optimally, and furthermore the sun glint masking algorithms assume a global mean wind speed of 6 m s^{-1}. This is probably a somewhat excessive estimate, as we have found the global mean to be closer to about 4.75 m s^{-1} [*Gregg and Patt*, 1994], based on 6 years of data from the Fleet Numerical Oceanography Center (1983-1988). The combination of cloud obscuration and excessive sun glint masking leads to loss of sampling in this region, in addition to errors introduced as a result of processing sun glint contaminated data when the wind speeds exceed the assumed global mean. The net result appears to be a substantial underestimate of chlorophyll concentrations by the CZCS. That sampling loss results in a bias is surprising, and suggests that there may be a great deal of growth occurring under cloudy skies.

The tropical Atlantic suffers from the same problems associated with clouds and sun glint as the tropical Pacific, but has additional difficulties from remote sensing as well. Two of these are the occurrence of a highly non-standard aerosol deriving from the Saharan Desert and terrigenous input of optically active suspended and dissolved materials from three major rivers, the Congo on the eastern side and the Amazon and Orinoco on the west. Saharan aerosols can be absorbing [*Carder et al.*, 1991], which confounds the atmospheric correction algorithms. Sometimes, especially in spring, expect then that the CZCS would overestimate chlorophyll here because of the presence of CDOM, but the *in situ* observations and blended analysis indicate the opposite. This effect of CDOM may be overwhelmed by the sampling biases occurring here due to clouds and sun glint, as in the tropical Pacific, and possibly by the presence of non-living suspended materials also deriving from the rivers [*Muller-Karger et al.*, 1988; *Smith and Demaster*, 1996].

The largest anomaly in the entire blended data set is the tropical and North Indian Oceans in the summer. The anomaly approached 140% in the tropical Indian. This is the season of the southwest monsoon, which brings with it intense wind (mean monthly speeds in excess of 10 m s^{-1} in August), and heavy cloud cover (exceeding 80%). Winds speeds are poorly treated in the CZCS data, with the effects of sun glint previously discussed but also foam/whitecap reflectance problems that are not accounted for in the algorithms. These factors, in addition to low CDOM upwelled waters, cloud obscuration, and sun glint are possible reasons for the large positive anomalies encountered here with the blended analysis. This is a heavily sampled region by *in situ* platforms, so the anomalies are unlikely to be due to sparseness. The results here suggest that the large chlorophyll concentrations detected by the CZCS in the tropical Indian Ocean, Arabian Sea, and Bay of Bengal during the southwest monsoon are even larger, as represented by the blended analysis. Interestingly, in winter, when the winds have diminished and the skies have cleared, the blended analysis suggests the CZCS overestimates here.

4.5. Northern Hemisphere

Overall, the blended analysis and the CZCS estimates are in better agreement in the Northern Hemisphere than in the rest of the world's oceans. Anomalies are often <10% regionally and are anomaly exists, and the western portion, where there is a strong positive anomaly. These conditions appear to be independent of season. English *et al.* [1996] compared sea truth data at Ocean Weather Station P and concluded that the CZCS overestimates chlorophyll. Our results agree with that assessment, but only as a local phenomenon. The rest of the Pacific in the blended analysis, except the northwestern seas, suggests that the CZCS underestimates.

The apparent systematic over- and underestimation of CZCS in the northeastern and northwestern Pacific, respectively, is perplexing. English *et al.* [1996] attribute the overestimation in the northeastern portion to cloud contamination and the effects of inadequate compensation for electronic overshoot [*Mueller*, 1988]. Analysis of ISCCP cloud cover, optical thickness, and cloud water path does appear to indicate denser clouds in the eastern portion of the North Pacific, where optical thickness of 8-12 is not uncommon along with cloud water paths exceeding 100 g m^{-2}. These are contrasted with typical optical thickness of 4 or less in the western portion and cloud water paths generally between 50 and 100 g m^{-2}. However, no meridional trend could be detected in cloud cover. Both sub-regions are impacted by persistently large cloud cover, typically 80% or more. With the electronic overshoot problems of the CZCS [*Mueller*, 1988], cloud thickness can have important effects. Coupled with few cloud-free opportunities to view the surface, these problems may be more severe in the eastern portion. This may be consistent with the net effect of cloud contamination/electronic overshoot to produce an overestimate in the CZCS data, as suggested by English *et al.* [1996].

Several authors have noted CZCS underestimates in comparison to *in situ* data in the Northern Hemisphere. Muller-Karger *et al.* [1990] and Mitchell *et al.* [1991] attributed the problem to clouds, data sparseness. Our constraint modifications greatly alleviate some of the shortcomings of the method as applied to chlorophyll, but extreme data sparseness, such as the South Atlantic Ocean in particular, are still prone to difficulties.

Nevertheless, the widespread use of the global CZCS data set and significant advances in understanding that have resulted from this data set justify its use here. Furthermore, coupled with accurate *in situ* data, which form an interior "truth" boundary condition into which the spatial variability of the CZCS is merged using the conditional relaxation analysis method, provides a limited error-correction of the satellite data. Thus we can improve on the accuracy of the CZCS data while spatially extending the applicability of *in situ* data to produce an overall improved data set. Our objective here is to provide a climatological view of global and regional chlorophyll data using the best features of satellite and *in situ* sampling platforms. Despite limitations due primarily to *in situ* and somewhat satellite data sparseness, we believe this blended data set achieves this objective, and provides a more representative view of global seasonal climatological chlorophyll. Further improvement requires enhancement of CZCS data for new advances in radiative transfer methodologies, better calibration, etc., while simultaneously acquiring more *in situ* data. Application of this method to present and future satellites, such as SeaWiFS and the Moderate Resolution Imaging Spectrometer is entirely appropriate, but requires availability of simultaneous *in situ* data.

Acknowledgements. We thank Richard Reynolds (NOAA/National Center for Environmental Prediction) for reviewing the manuscript and providing significant improvements. We would like to thank all the contributors of chlorophyll data to NODC who have made this work possible. CZCS

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The final blended chlorophyll is produced by piecing together the results of the individual blended analyses according to the biomass domains.

Figure 2. Seasonal chlorophyll biomass domains defined by CZCS abundance, that constrain *in situ* and satellite data blending. Domain 1 is the mid-ocean gyre region, Domain 2 is equatorial upwelling, Domain 3 indicates the high chlorophyll coastal, polar, and sub-polar regions. The open ocean gyres (Domain 1) are clearly distinguished from high abundance upwelling, coastal, and high latitude domains. Coastal domains are shown separately merely for reference (Domain 4), but they have no effect on the results: they are included as high chlorophyll domains (Domain 3) in the blended analysis. Note the changes in the biomass domain dimensions and locations by season.

Figure 3. Illustration of the effects of the log-transform and domain restrictions on the blended analysis. A section of North America is depicted, with longitude labeled on the x-axis and latitude on the y-axis. Top: The blended analysis without log-transform and without domain restrictions. Middle: Blended analysis with transformed data but no restrictions on domain. Bottom: transformed data with domain restrictions.

Figure 4. Spatial coverage by *in situ* (top) and CZCS (bottom) platforms for the years 1979-1986. A single ordinate tick-mark represents 1% of the global ocean for *in situ* data and 50% for CZCS data. *In situ* data provide 1-3% ocean coverage but are consistent for the 8-year period. These percentages refer to the amount of the global ocean that have samples within the 1°-by-1° spatial grids. CZCS data provide much larger spatial coverage (>50% in some seasons and years), but its limited duty cycle produces variable observational patterns.

Figure 5. Global comparison between blended chlorophyll analysis and CZCS estimates by season (mg m^{-3}). The blended analysis produces globally larger chlorophyll concentrations, and changes the seasonal distribution. It exhibits a spring global maximum in contrast to the CZCS, which indicates an autumn maximum.

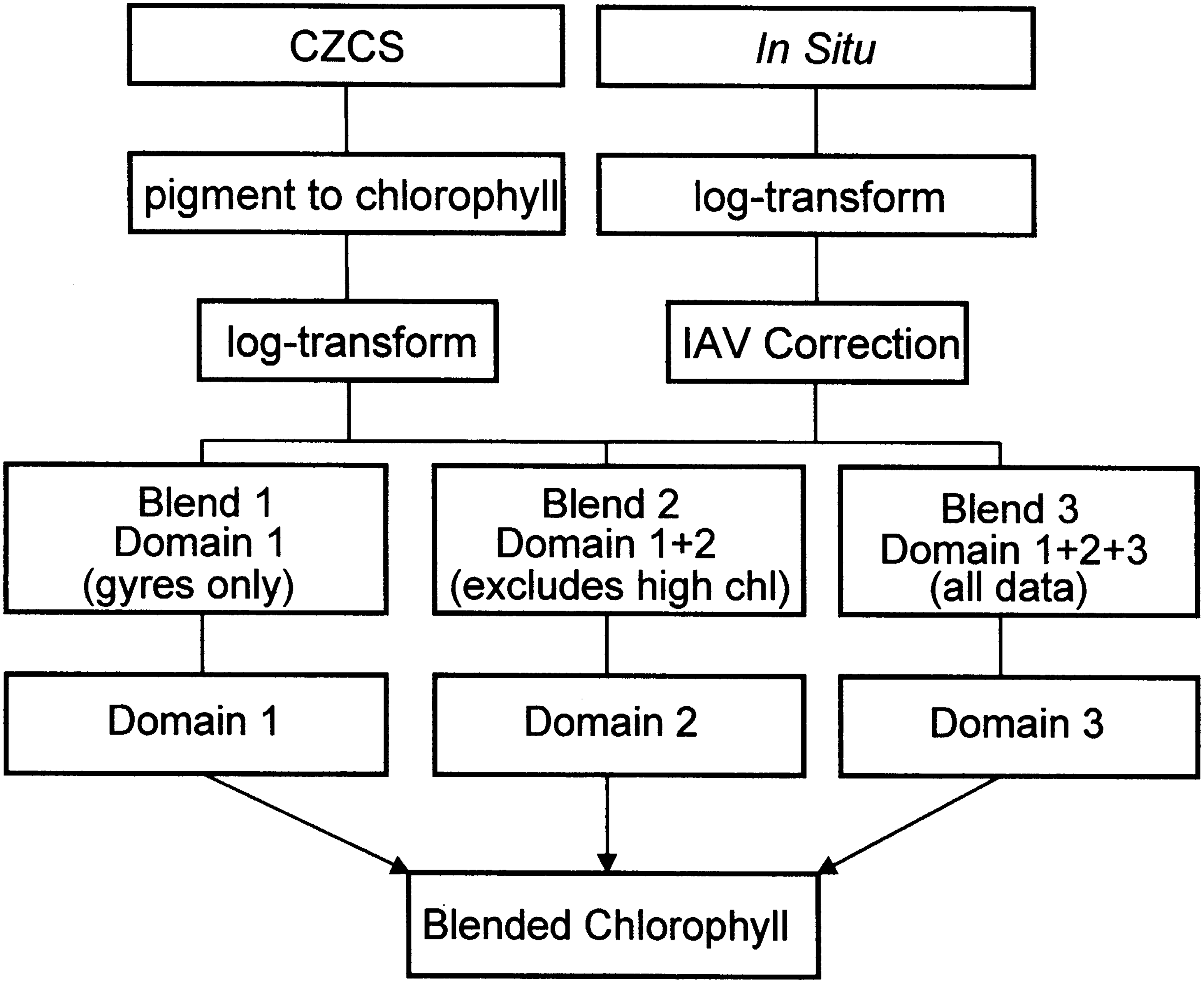
Figure 6. Regional comparison of chlorophyll estimated by the blended analysis and the CZCS, by season. Differences are expressed as blended - CZCS in percent (of CZCS)

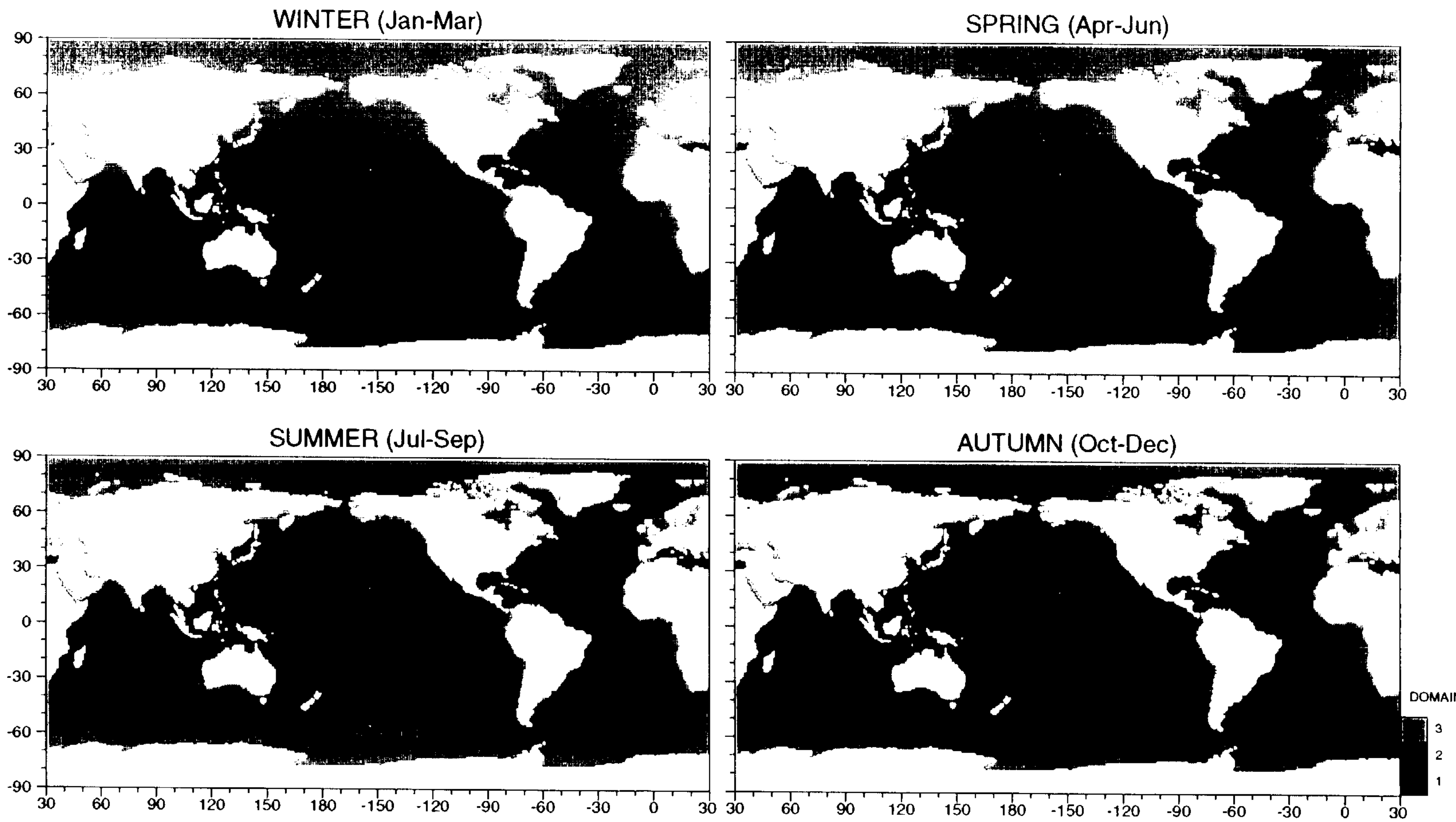
Figure 7. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for winter (January-March; mg m^{-3}). Anomaly indicates blended – CZCS. *In situ* observations have been expanded to enhance visibility. The color chart to the right of the *in situ* plot applies to the CZCS, *in situ*, and blended figures, and the anomaly field color chart is shown to the right of the anomaly field plot (in percent).

Figure 8. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for spring (April-June).

Figure 9. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for summer (July-September).

Blended Method





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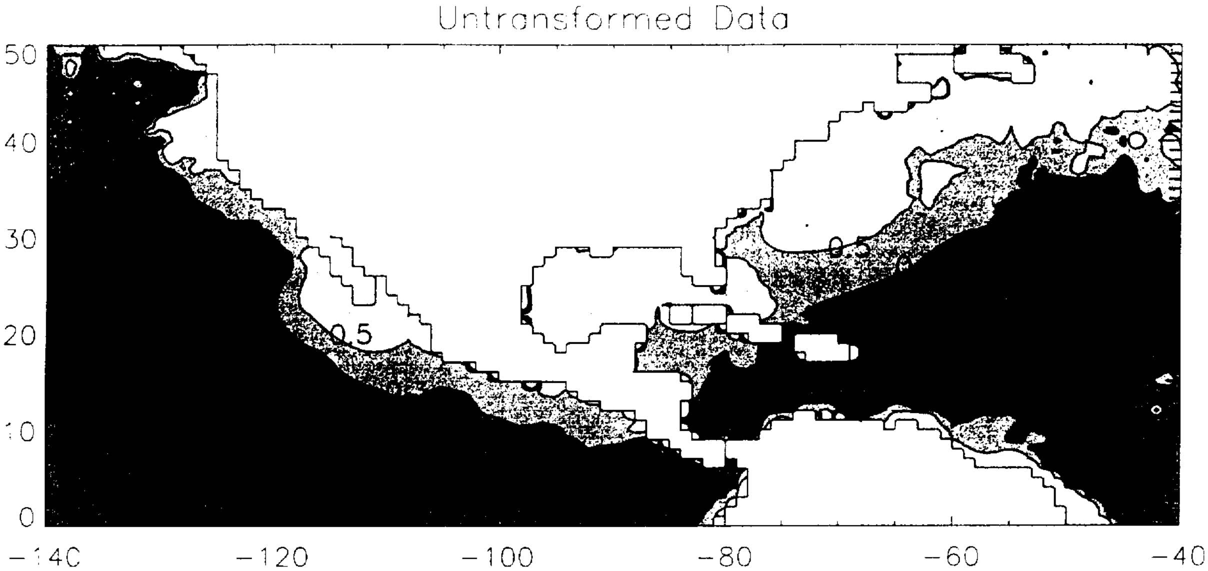
SPRING (Apr-Jun)
SUMMER (Jul-Sep)
AUTUMN (Oct-Dec)
DOMAIN
3
2
1


Untransformed Data
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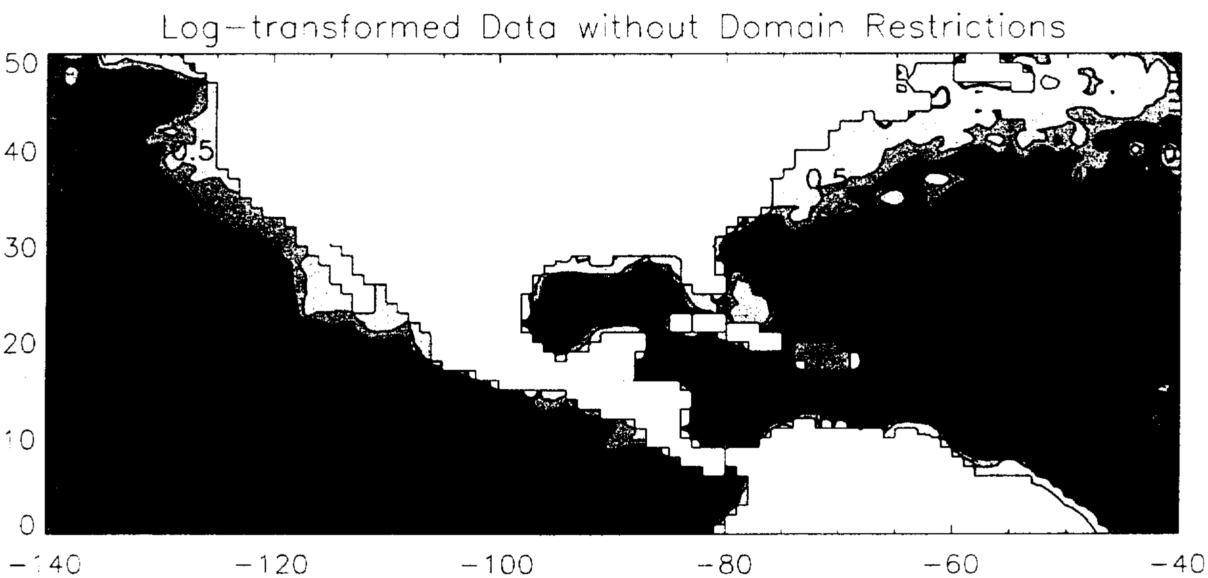
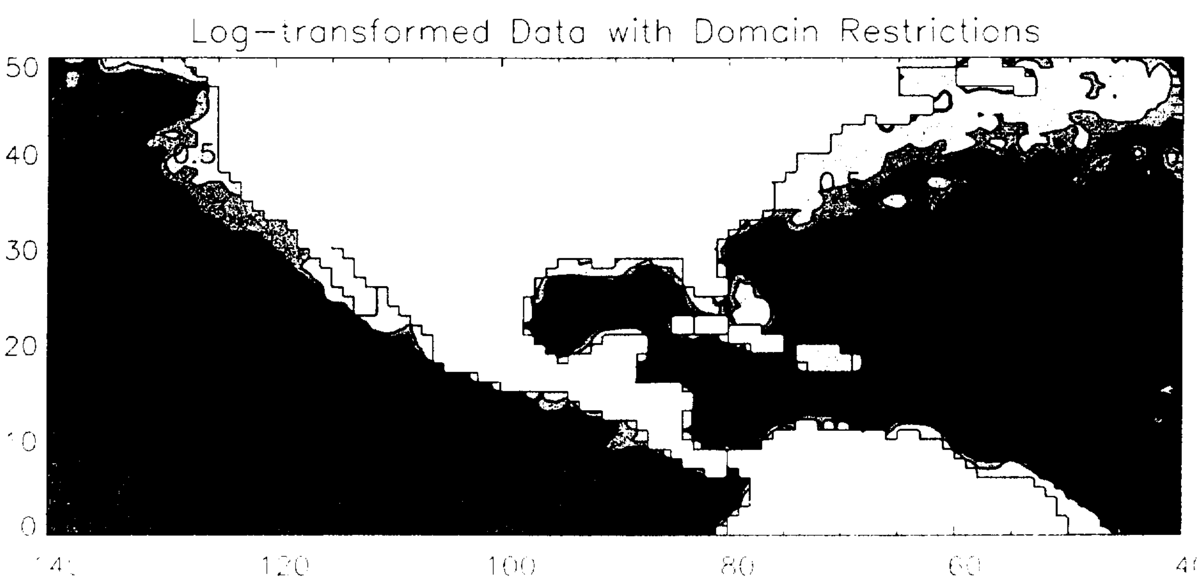
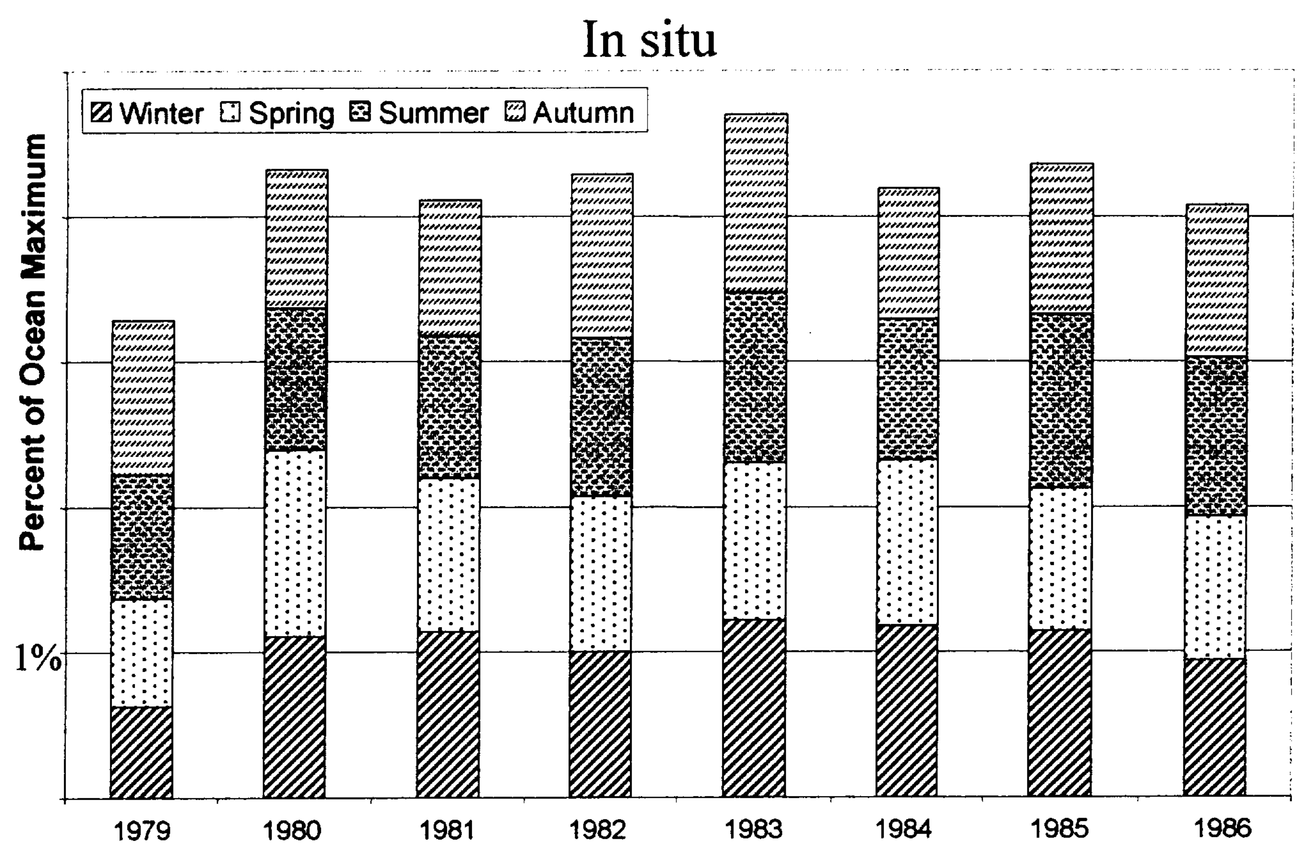
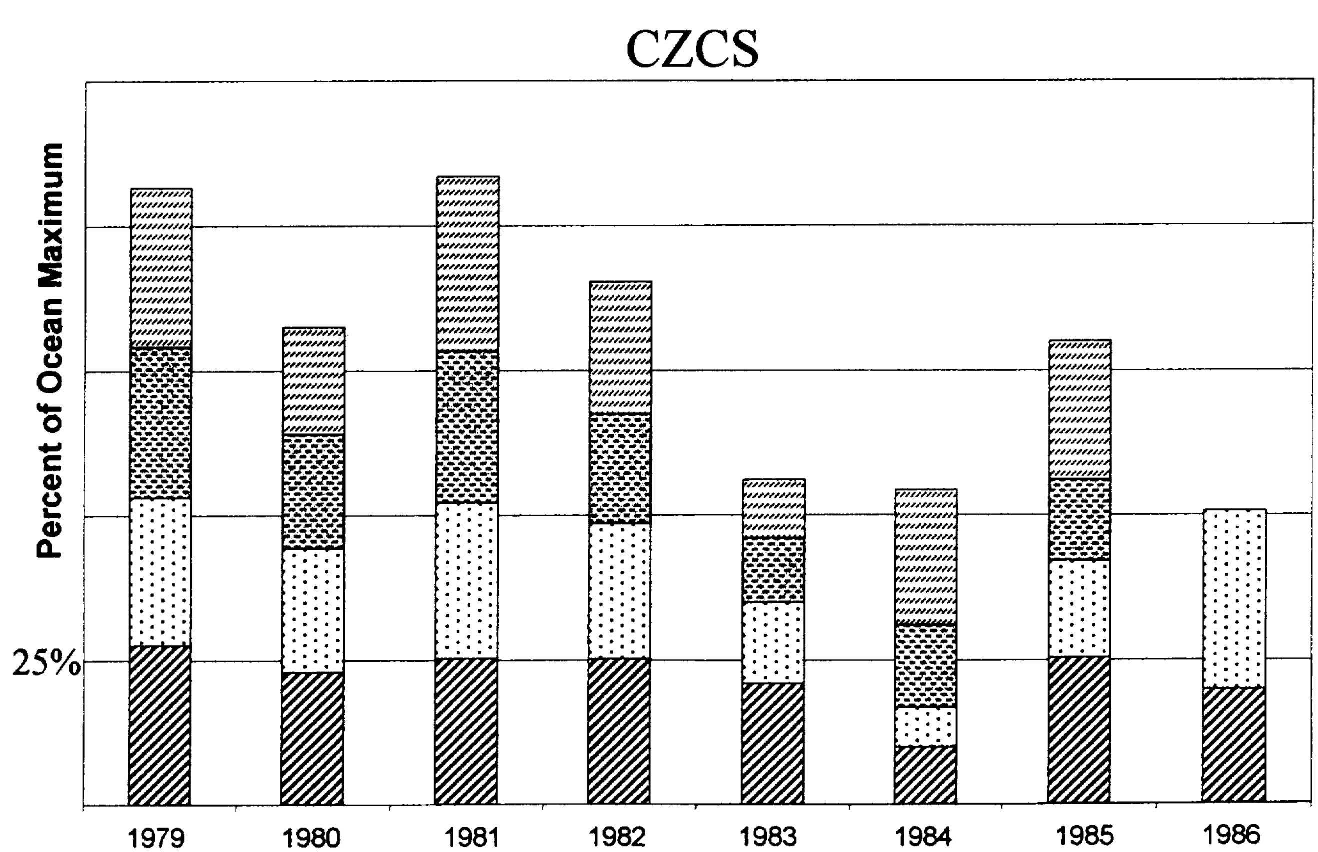
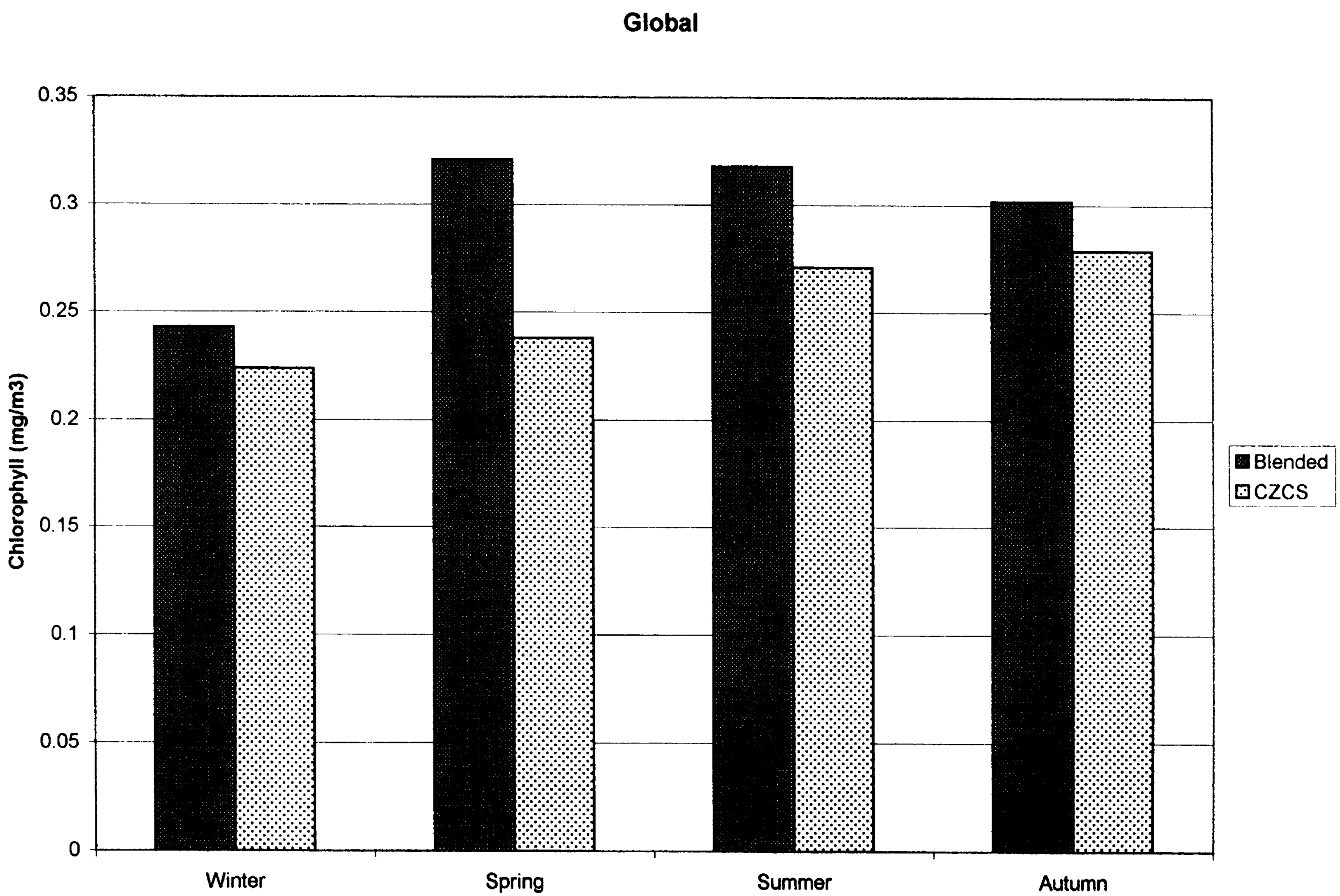
−40

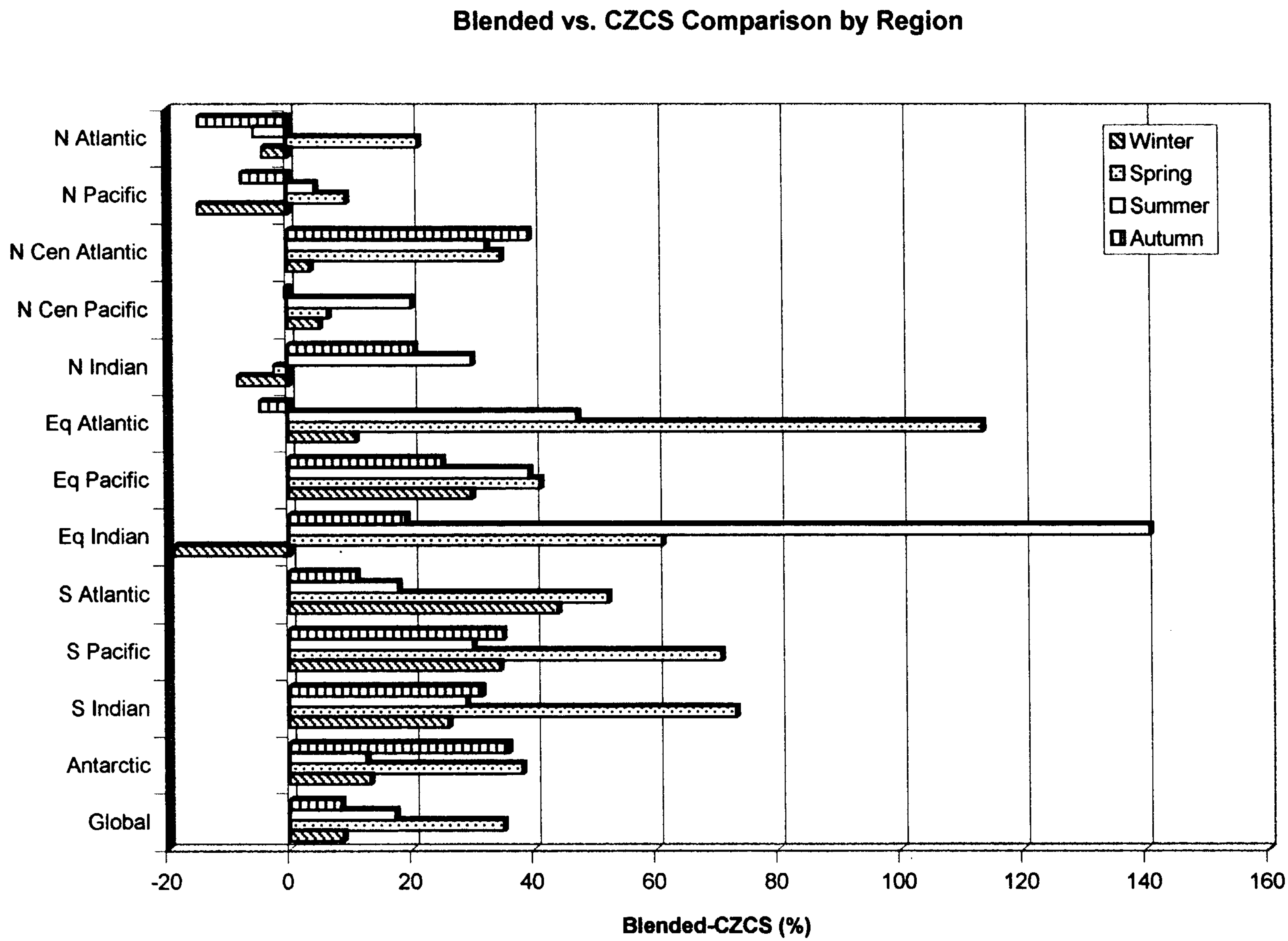

Log−transformed Data without Domain Restrictions
50
40
30
20
10
0
0.5
0.5
−140
−120
−100
−80
−60
−40

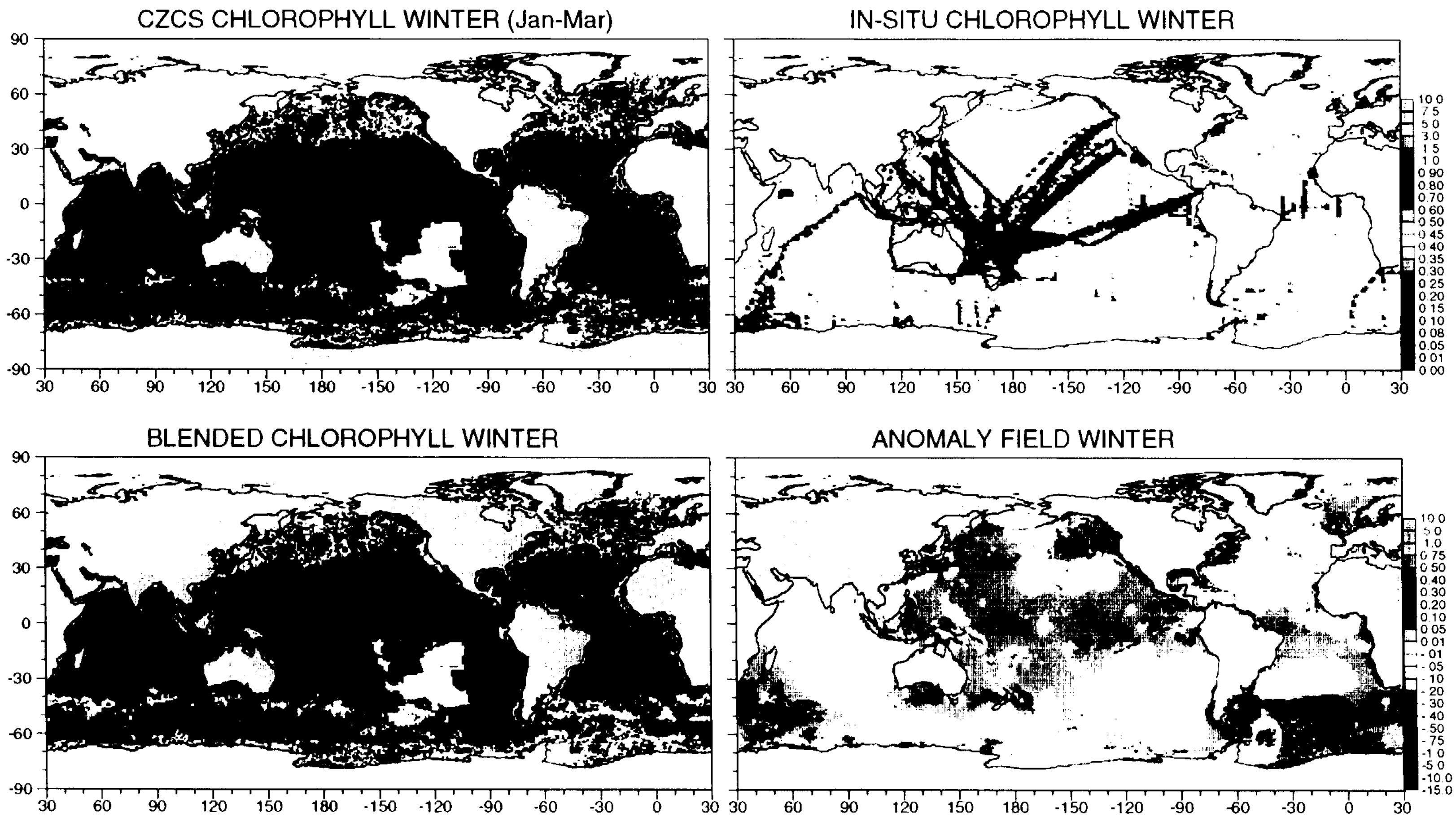

Log−transformed Data with Domain Restrictions
50
40
30
20
10
0
0.5
120
100
80
60

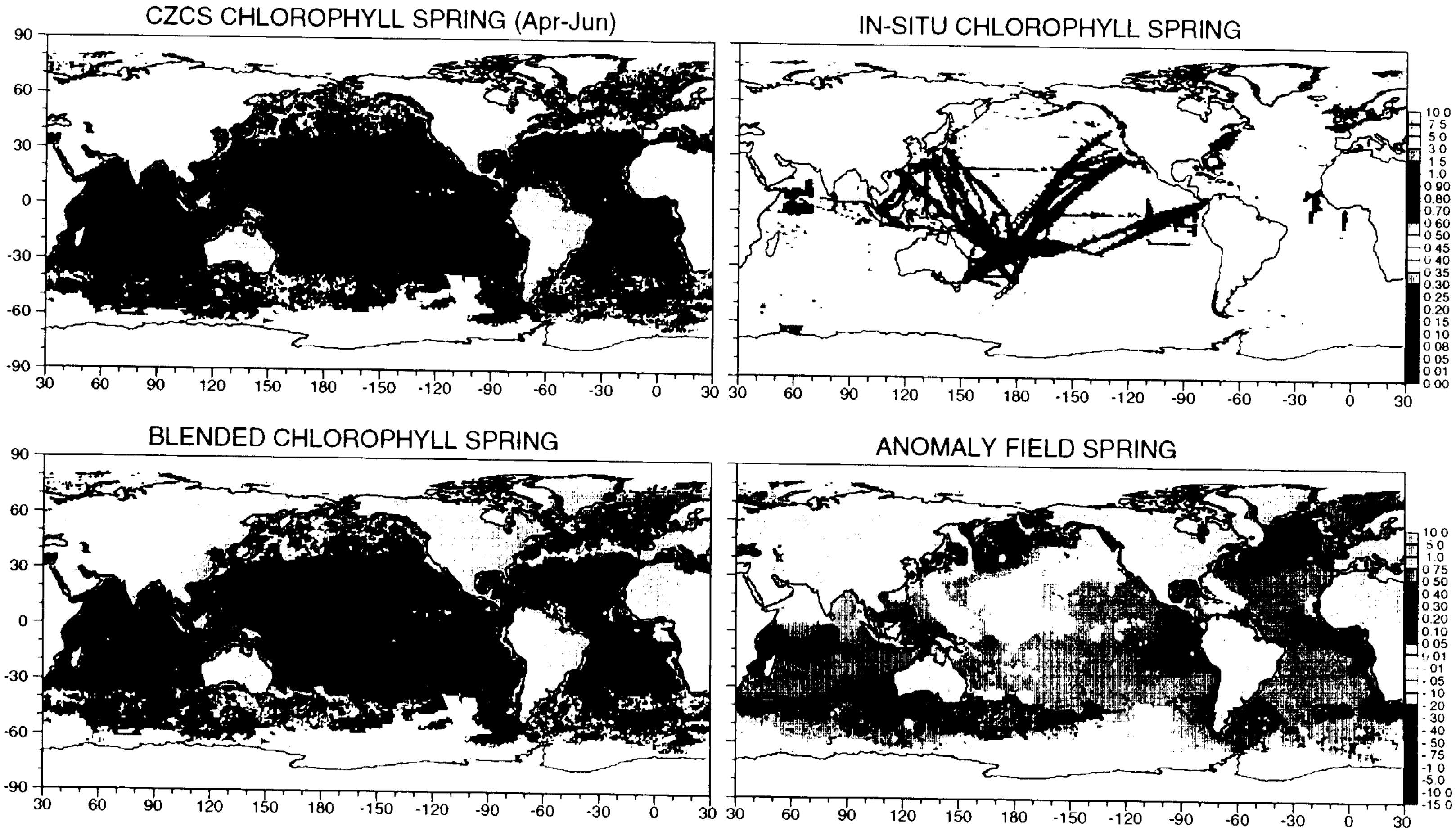

In situ
Winter
Spring
Summer
Autumn
Percent of Ocean Maximum
1%
1979
1980
1981
1982
1983
1984
1985
1986

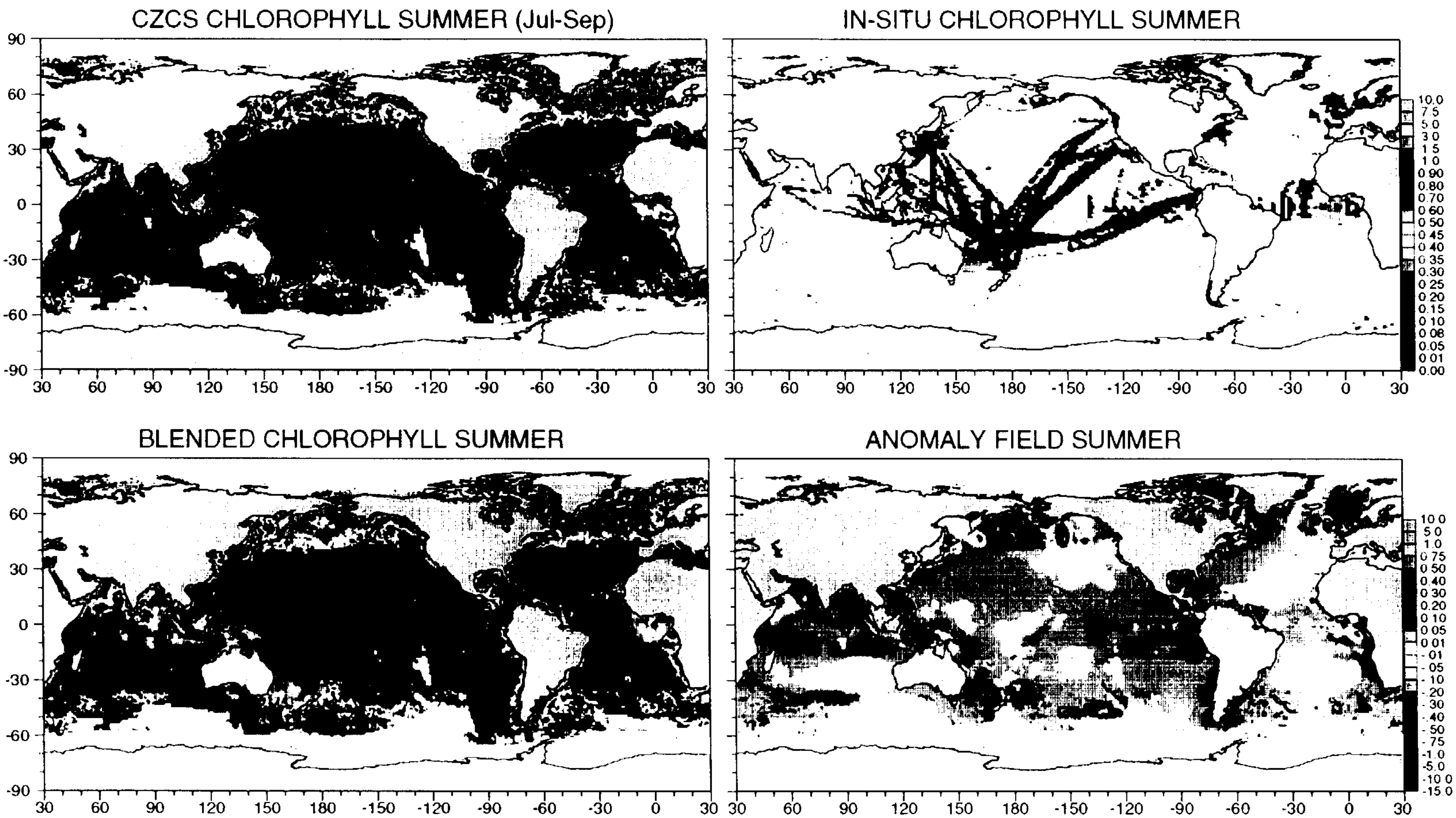

CZCS
Percent of Ocean Maximum
25%
1979
1980
1981
1982
1983
1984
1985
1986

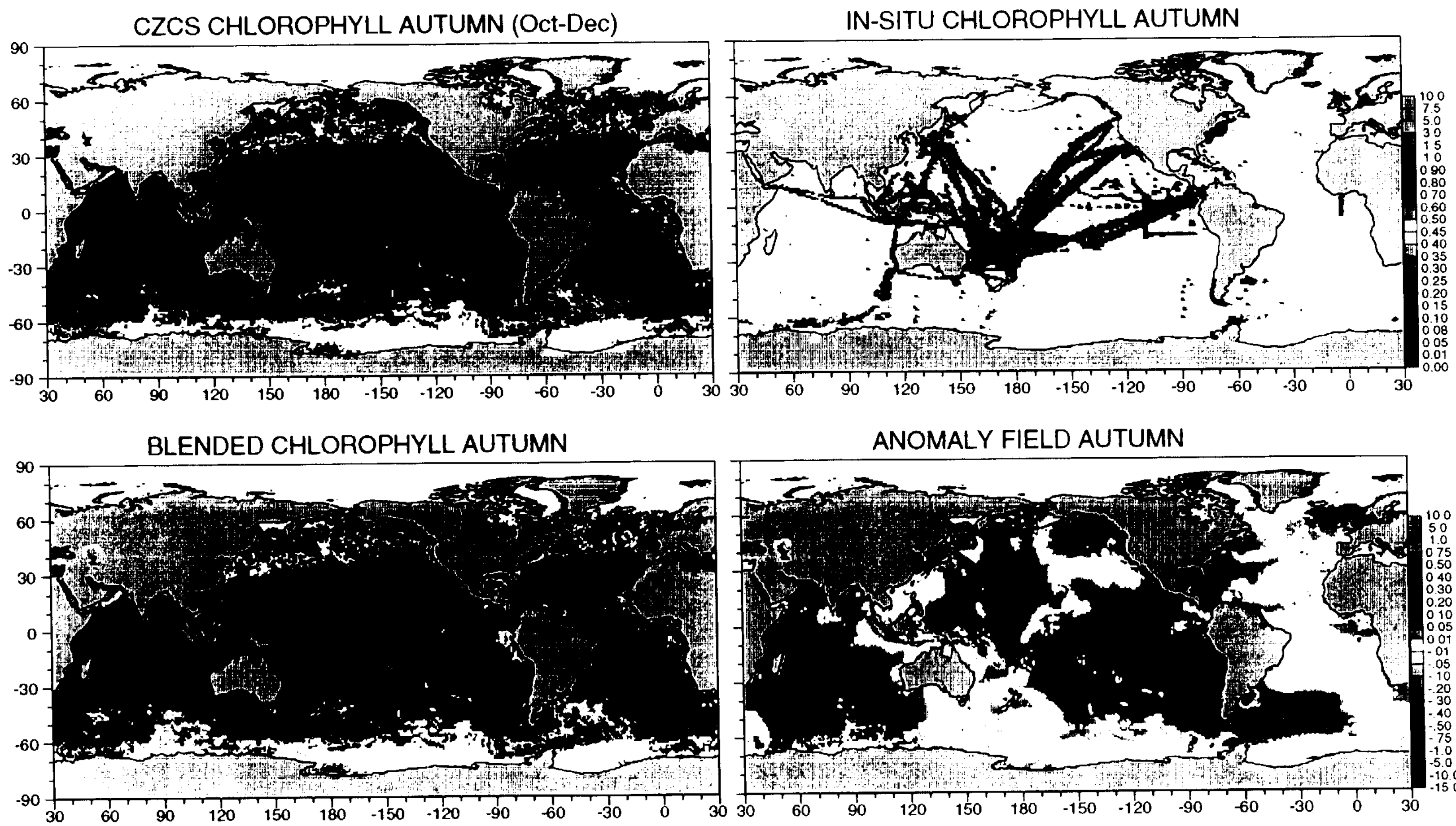

Global
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Chlorophyll (mg/m3)
Winter
Spring
Summer
Autumn
Blended
CZCS


Blended vs. CZCS Comparison by Region
N Atlantic
N Pacific
N Cen Atlantic
N Cen Pacific
N Indian
Eq Atlantic
Eq Pacific
Eq Indian
S Atlantic
S Pacific
S Indian
Antarctic
Global
Winter
Spring
Summer
Autumn
-20
0
20
40
60
80
100
120
140
160
Blended-CZCS (%)


CZCS CHLOROPHYLL WINTER (Jan-Mar)
IN-SITU CHLOROPHYLL WINTER
BLENDED CHLOROPHYLL WINTER
ANOMALY FIELD WINTER
90
60
30
0
-30
-60
-90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30
10.0 7.5 5.0 3.0 1.5 1.0 0.90 0.80 0.70 0.60 0.50 0.45 0.40 0.35 0.30 0.25 0.20 0.15 0.10 0.08 0.05 0.01 0.00
10.0 5.0 1.0 0.75 0.50 0.40 0.30 0.20 0.10 0.05 0.01 -.01 -.05 -.10 -.20 -.30 -.40 -.50 -.75 -1.0 -5.0 -10.0 -15.0


CZCS CHLOROPHYLL SPRING (Apr-Jun)
IN-SITU CHLOROPHYLL SPRING
BLENDED CHLOROPHYLL SPRING
ANOMALY FIELD SPRING
90
60
30
0
-30
-60
-90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30
10 0
7 5
5 0
3 0
1 5
1.0
0 90
0.80
0.70
0 60
0 50
0 45
0 40
0 35
0.30
0 25
0.20
0 15
0 10
0 08
0 05
0 01
0 00
10 0
5 0
1.0
0 75
0 50
0 40
0.30
0.20
0.10
0 05
0 01
- 01
- 05
- 10
- 20
- 30
- 40
- 50
- 75
-1 0
-5.0
-10 0
-15 0


CZCS CHLOROPHYLL SUMMER (Jul-Sep)
IN-SITU CHLOROPHYLL SUMMER
BLENDED CHLOROPHYLL SUMMER
ANOMALY FIELD SUMMER
90 60 30 0 -30 -60 -90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30
10.0 7.5 5.0 3.0 1.5 1.0 0.90 0.80 0.70 0.60 0.50 0.45 0.40 0.35 0.30 0.25 0.20 0.15 0.10 0.08 0.05 0.01 0.00
10.0 5.0 1.0 0.75 0.50 0.40 0.30 0.20 0.10 0.05 0.01 -.01 -.05 -.10 -.20 -.30 -.40 -.50 -.75 -1.0 -5.0 -10.0 -15.0


CZCS CHLOROPHYLL AUTUMN (Oct-Dec)
IN-SITU CHLOROPHYLL AUTUMN
BLENDED CHLOROPHYLL AUTUMN
ANOMALY FIELD AUTUMN
90
60
30
0
-30
-60
-90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30