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Seasonal distributions of satellite-measured phytoplankton pigment concentration along the Chilean coast

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Abstract. Five years (1979-1983) of Coastal Zone Color Scanner satellite ocean color data are used to examine seasonal patterns of phytoplankton pigment concentration along the Chilean coast from 20°S to 45°S. Four kilometer resolution, 2-4 day composites document the presence of filaments of elevated pigment concentration extending offshore throughout the study area, with maximum offshore extension at higher latitudes. In three years, 1979, 1981, and 1983, sufficient data exist in monthly composites to allow recreation of portions of the seasonal cycle. Data in 1979 are the most complete. Near-shore concentrations and cross-shelf extension of pigment concentrations in 1979 are maximum in austral winter throughout the study area and minimum in summer. Available data from 1981 and 1983 are consistent with this temporal pattern but with concentrations approximately double those of 1979. Seasonal, spatial patterns within 10 km of shore and 50 km offshore indicate a latitudinal discontinuity both in absolute concentration and in the magnitude of the seasonal cycle at approximately 33°S in both 1979 and in the climatological time series. The discontinuity is strongest in fall-winter and weakest in summer. South of this latitude, concentrations are relatively high (2-3 mg m^{-3} in 1979), a strong seasonal cycle is present, and patterns 50 km offshore are correlated with those within 10 km of shore. North of 33°S, concentrations are < 1.5 mg m^{-3} (in 1979), and the seasonal cycle within 10 km of shore is present but much weaker and less obviously correlated with that 50 km offshore. The seasonal cycle of pigment concentrations is 180° out of phase with monthly averaged upwelling favorable winds. Noncoincident Pathfinder sea surface temperature data show that over most latitudes, coastal low surface temperatures lag wind forcing by 1-2 months, but these too are out of phase with the pigment seasonal cycle. These data point to control of pigment patterns along the Chilean coast by the interaction of upwelling with circulation patterns unconnected to local wind forcing.

1. Introduction

Dominant equatorward alongshore wind stress in eastern boundary current regions induces an offshore surface Ekman transport, surface divergence along the coastal boundary, and the upwelling of relatively cold, nutrient-rich water nearshore. Seasonal cycles in basin-scale atmospheric forcing and continental heating / cooling impose a latitudinally dependent seasonal cycle on local wind forcing [*Bakun and Nelson*, 1991]. The upwelling results in increased primary productivity and elevated near-surface phytoplankton biomass. The coastal region of elevated chlorophyll concentrations and cold surface temperatures is typically separated by a frontal zone from offshore, stratified, more oligotrophic conditions [*Kosro et al.*, 1991; *Hood et al.*, 1991]. Previous work in the California Current and Benguela Current [*Strub et al.*, 1991; *Duncombe Rae et al.*, 1992] has shown that the orientation and cross-shelf position of the upwelling front and the associated distributions of elevated chlorophyll concentrations can be strongly modulated by the mesoscale dynamics of the region. These dynamics can result in filaments of elevated pigment concentration extending hundreds of kilometers offshore and an offshore expansion of coastal surface characteristics to cross-shelf scales larger than those expected simply from local wind-driven dynamics. The strong surface gradients of temperature and phytoplankton pigment concentration present during upwelling conditions in eastern boundary currents and their evolution in time and space are clearly evident in satellite data [e.g., *Pelaez and McGowan*, 1986; *Strub et al.*, 1991; *Van Camp et al.*, 1991].

Wind-driven upwelling in the Peru-Chile Current system supports one of the most biologically productive fisheries on the planet [*Food and Agriculture Organization (FAO)*, 1992]. Along the Chilean coast, however, systematic analyses of the large-scale variability of phytoplankton pigment patterns associated with this forcing are relatively few. In a recent review, *Abbott and Barksdale* [1995] state that extensive cross-shelf filaments have been observed in three of the eastern boundary current regions but leave the Chilean region unmentioned. In the California Current and also, but to a lesser extent, in the Canary and Benguela Current regions, patterns in sea surface temperature (SST) and ocean color satellite data have been the subject of numerous studies examining relationships between physical forcing and biological response [e.g., *Abbott and Zion*, 1987; *Thomas and Strub*, 1989; *Strub et al.*, 1990; *Van Camp et al.*, 1991; *Weeks and Shillington*, 1994]. *Fonseca* [1989] shows surface

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temperature patterns which appear similar to those evident off California but notes that cold plumes extend as far as 50-100 km offshore, substantially less than their California Current counterparts [*Abbott and Barksdale*, 1991]. Time series of satellite imagery show a strong seasonal cycle in SST in the region closest to shore along the northern Chilean coast (to 23°S) [*Barbieri et al.*, 1995] with coldest coastal temperatures present during austral winter and farthest offshore extension of upwelling features in summer. These authors show that surface temperature filaments are present most often in summer. Along the central Chilean coast (32°-35°S), *Yáñez et al.* [1996a, b] show the surface temperature front associated with commercial fish habitat extends over 100 km offshore. The relationship of large-scale SST patterns to phytoplankton distributions, however, is unknown.

A preliminary analysis of the Chilean coast using satellite ocean color data from the Coastal Zone Color Scanner (CZCS) [*Thomas et al.*, 1994] suggests that although large-scale seasonal / latitudinal patterns of upwelling-favorable wind forcing are very similar to those in the California Current [*Bakun and Nelson*, 1991; *Thomas et al.*, 1994], the climatological seasonal patterns of pigment distribution along the Chilean coast are different. This analysis, however, was performed on the global CZCS data set released by NASA on CD-ROM in 1992, available only as monthly means and 20 km pixels. While such a data set is suitable for analyses of large-scale temporal and spatial variability, it is incapable of assessing processes which occur very close to the coast and/or might not be spatially/temporally persistent (e.g., filaments). All high temporal and spatial frequency information is lost. For patterns within 20 km of the coast, no analysis at all is possible. Individual uncalibrated CZCS scenes presented by *Uribe and Neshyba* [1983] and *Espinoza et al.* [1983] suggest that on occasion, filaments of elevated pigment concentration extend 200-400 km offshore of the Chilean coast in the region 30°S to 40°S. *Fonseca and Farias* [1987] show that filaments extend 200-300 km offshore and that five upwelling centers are evident, centered at 20°, 23°, 30°, 33°, and 37°S. The large-scale latitudinal or cross-shelf pattern of seasonal cycles, however, remains poorly described and understood. Similarly, the extent to which pigment concentrations form filaments contributing to mean cross-shelf patterns remains poorly described. We do know, however, from extensive work in the California Current, that knowledge of these patterns provides significant insight into regional biological and physical processes and their linkages as well as connections between these eastern boundary current coastal/shelf regions and adjacent open ocean/deep basins.

In this paper, a higher resolution CZCS data set than that examined by *Thomas et al.* [1994] is used to provide a systematic examination of cross and alongshelf patterns of phytoplankton pigment concentration along the Chilean coast. The study area is from ~18.5°S to 45°S, the region in which seasonal persistent equatorward wind stress is a feature but north of the complicating influence of the southern fjord region (Figure 1). A series of questions focuses attention on latitudinal and seasonal variability. Do filaments of elevated phytoplankton pigment occur, and, if so, what are typical length scales? What is the cross-shelf distribution of pigment concentration in the Chilean coastal region, especially within 100 km of the coast? Do these have a seasonal cycle? If so, does the seasonal cycle change with latitude? What is the relationship of the above to wind forcing and surface temperature with regard to latitude and season? How do the higher-resolution coastal patterns contribute to the climatological large-scale picture presented by *Thomas et al.* [1994]?

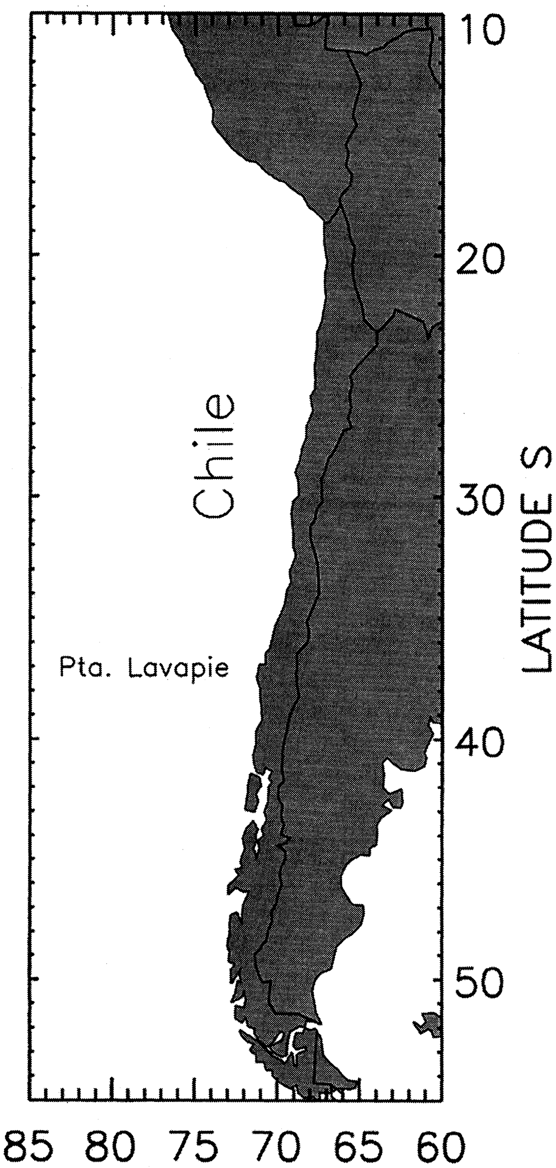

Figure 1. The Pacific coast of South America showing the study area off the coast of Chile from 18.5°S to 45°S.

2. Data and Methods

CZCS data are available from late 1978 to mid-1986; however, both data coverage and sensor stability were not constant over this period [*Evans and Gordon*, 1994]. *Evans and Gordon* [1994] show that data in the later years of the mission suffered most heavily from degradation. For this study, all 4 km resolution Level 2 scenes from the period 1979-1983 were obtained from the NASA Goddard Space Flight Center archive. These were remapped to a standard projection to include the study area from 18.5° to 45°S and offshore to 90°W (Figure 1). Scenes from the same day were then reformed into a single image in units of satellite-measured pigment concentration to produce a time series of daily images with approximately 4 km spatial resolution.

Previous examination of the CZCS time series in eastern boundary current regions [*Abbott and Zion*, 1987] has shown that images are not randomly spaced in time but are biased toward specific weather conditions. Clear images occur in groups separated by weather events (clouds). Decorrelation time scales in regions of active upwelling, at least in the California Current, are approximately 3 days [*Kelly*, 1985; *Denman and Abbott*, 1994]. To obtain improved visualizations of "instantaneous" pigment patterns along the Chilean coast, images collected within 1-4 days of each other were composited together. Relatively cloud-free examples of these images are examined for the presence, location, and general characteristics of any filaments.

Seasonal and latitudinal variability is examined by forming monthly composites from the daily scenes, retaining the 4 km spatial resolution and using all available scenes, resulting in 12 scenes for each study year. Statistically more robust methods for forming temporal composites from irregular time series have been demonstrated [*Chelton and Schlax*, 1991]. However, this method requires a priori knowledge of the temporal decorrelation scales, which are not known for this area. Furthermore, examination of the resultant monthly time series showed that sufficient data to recreate a complete seasonal cycle exist in only one of the study years (1979), with partial seasonal cycles possible in two other years (1981 and 1983). Missing data in 1980 and 1982 are too extensive to allow meaningful reconstruction of any seasonal cycle.

Seasonal patterns of pigment concentration are examined in two ways, as a function of cross-shelf distribution and as a function of latitude. Cross-shelf profiles of CZCS-measured phytoplankton pigment concentration were constructed by subsampling the monthly composite scenes at specific latitudes beginning at the pixel closest to the coast and progressing west. Because of Chilean coastal orientation, zonal sampling closely approximates a transect perpendicular to the coast. Each cross-shelf transect is a mean of pigment concentrations equidistant from the coast over a distance of 200 km north and south of the sampling latitude, creating a 400 km wide sampling transect. This provides cross-shelf profiles representative of mean conditions over relatively large sections of the coast, reduces (but does not eliminate) gaps in the time series due to missing data, and smoothes extreme values. Latitudinal variability of the seasonal cycle is examined by subsampling the monthly time series into cross-shelf means over approximately 10 km (3 pixels) at each pixel in latitude, forming a pigment profile for each month as a function of latitude. Missing data in this time series were filled by two steps of linear interpolation. First, spatial interpolation over latitudinal distances of 100 km within the month of missing data was carried out. Gaps still present after spatial interpolation were then filled by temporal interpolation between adjacent months. No gaps remained in the data set after these two steps.

The CZCS data are known to contain errors and biases. These are discussed in some detail by *Strub et al.* [1990] and *Evans and Gordon* [1994] and are not repeated here. The accuracy of the data is discussed by *Abbott and Zion* [1987]. *Chavez* [1995] shows that climatological mean CZCS pigment concentrations off Peru appear significantly lower than ship-measured estimates. The extent to which these climatological CZCS data are biased by the interaction of missing data and interannual variability is unknown. Although constraining, these factors do not prevent the questions posed here, focused on relative patterns and spatial scales, from being addressed.

Two other data sets are used for comparisons with the CZCS data. Wind data are the twice daily 2.5° resolution surface vector products from the European Centre for Medium-Range Weather Forecasts (ECMWF). These data were subset to the study area, and wind stress was calculated, interpolated to points 100 km offshore, and then formed into temporal means. Data are from 1979 to 1988, covering the CZCS mission period. Sea surface temperatures (SSTs) calculated from advanced very high resolution radiometer data covering the entire Chilean coast are available from the Pathfinder program at 9 km resolution. This product, however, does not overlap with the CZCS mission period. Data from 1987 to 1993 are used to form a monthly climatology for comparison to seasonal patterns evident in the CZCS data.

3. Results

3.1. Filaments

Image composites over 1-4 days are used to address the question of whether filaments of high pigment concentration extend offshore from the Chilean upwelling system and, if so, whether they develop length scales similar to those evident in the California Current system. Missing data in the Chilean region are such that a systematic quantitative analysis of filament length and variability to compare with that carried out by *Abbott and Barksdale* [1991] for California, or *Hayes et al.* [1993] for the Iberian peninsula, is not possible. The available images are sufficient, however, to document the presence and general nature of filaments in the Chilean upwelling region.

All images were examined. Subjectively chosen, relatively cloud-free examples showing CZCS-measured pigment patterns are shown in Plate 1 using images from five different years. All images show elevated phytoplankton concentrations (> 0.5 mg m^{-3}) adjacent to the coast, more oligotrophic surface waters offshore, and concentrations > 1.0 mg m^{-3} in localized coastal upwelling centers. Elevated pigment concentrations originating near the coast extend offshore as filaments from many locations along the Chilean coast. In general, these appear to be shorter at lower latitudes, and the cross-shelf width of elevated pigment concentrations appears least at lower latitudes. The extent of missing data, especially at lower latitudes, even in these subjectively chosen images, is obvious. The pigment patterns also provide evidence of intense mesoscale circulation within the first 400 km from the coast, including well-developed eddies and dipole eddies. The images from March and April 1979 (year days 087-089 and 109-110, respectively) show concentrations > 0.5 mg m^{-3} extend up to 300 km offshore south of 38°S and over 500 km offshore in the vicinity of 35°S with highest coastal concentrations centered at the prominent headland at approximately 37°S. Filaments exist north of this but have lower concentrations and are shorter. The January image from 1980 (year days 011-014) shows eddies within 150 km of the coast and highest coastal pigment concentrations centered at 35°S and at 27°S. Concentrations > 3.0 mg m^{-3} extend 200 km offshore at 35°S. Originating at approximately 34°S, a thin

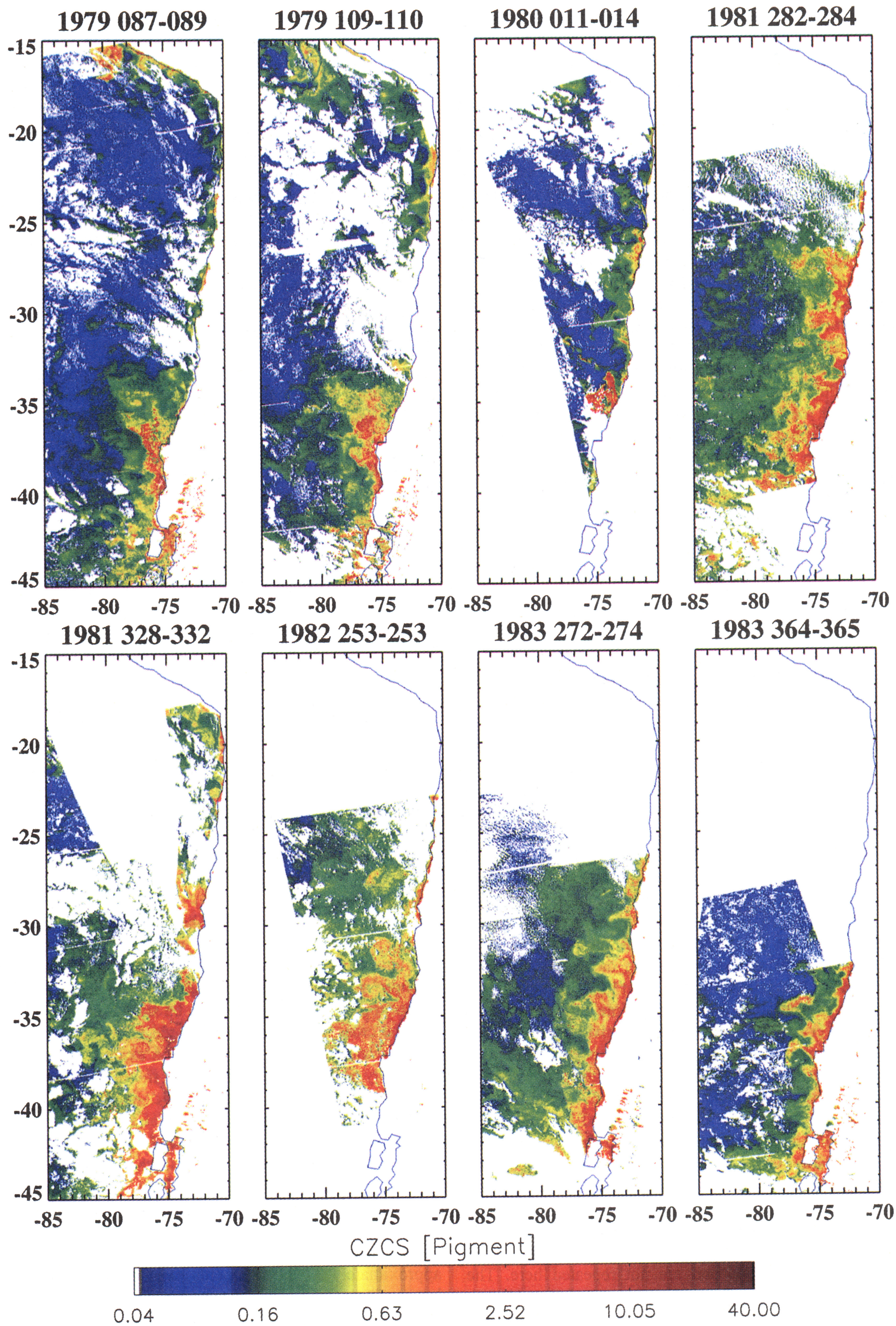

Plate 1. Examples of Coastal Zone Color Scanner image composites over 1-4 days from five different years, showing the presence and position of ocean color features along the Chilean coast, including the location and extent of filaments.

filament extends over 400 km in a northwest direction, terminating in an eddy at 80°W. The images from October and November 1981 (year days 282-284 and 328-332, respectively) show higher concentrations throughout the study area than were present in 1979 and 1980. Immediately adjacent to the coast, concentrations are never < 0.2 mg m^{-3}. Filaments with concentrations > 1.5 mg m^{-3} extend approximately 300 km offshore along the coast between 27° and 40° S (45°S in November). These concentrations extend over 400 km offshore in filaments centered at 27°S and 40°S in October and at 36°S in November. In September 1982 (year day 253), pigment concentrations > 1.0 mg m^{-3} extend over 300 km offshore in filaments centered at four latitudes, 36°, 34°, 32°, and 27°S. The images from September and December 1983 (year days 272-274 and 364-365, respectively) contrast austral spring and summer conditions. Unfortunately, no cloud-free ocean is visible north of 26°S. South of this, however, both images show extensive filament development. In September, coastal concentrations are higher and there are more filaments, extending further offshore than in December. Pigment concentrations > 1.0 mg m^{-3} extend over 250 km offshore south of 31°S but appear shorter north of this. Diffuse patterns with concentrations > 0.25 mg m^{-3} extend to the far western edge of the image (90°W) in September at 37°-38°S.

3.2. Seasonal Cross-Shelf Patterns

The monthly image time series from 1979, 1981, and 1983 are sufficient to construct at least partial seasonal cycles of cross-shelf pigment concentration. The seasonal cycles of cross-shelf pigment distribution constructed from transects centered at six latitudes covering the range of the study area for these years are shown in Figures 2, 3, and 4. Data from 1979 provide the most complete coverage (Figure 2), allowing construction of the cross-shelf pigment patterns in all 12 months at four of the study latitudes, with two months and one month missing from the two lowest latitude transects, respectively. The general seasonal cycle is similar throughout the latitudinal range of the study area, with maximum nearshore pigment concentrations and maximum cross-shelf extension of elevated pigment concentrations centered in austral winter (May, June, July, August). Relatively oligotrophic surface water (< 0.25 mg m^{-3}) intrudes closest to the coast during summer and fall (December – April). Concentrations and cross-shelf extension are minimum at 20°S, with > 1.0 mg m^{-3} found only within 10 km of the coast and only during June. At 25° S, concentrations > 1.0 mg m^{-3} extend up to 15 km offshore and are present in both June and February. Winter (June, July, August) is the most sustained period in which concentrations > 0.25 mg m^{-3} extend over 100 km offshore. The transects at 30°S show concentrations > 1.0 mg m^{-3} are also restricted to within 15 km of the coast and are present in May and June but also in December. Concentrations > 0.5 mg m^{-3} extend more than 100 km offshore in May and October with oligotrophic conditions (< 0.25 mg m^{-3}) within 100 km of the coast most prevalent in summer (January-April and December). The seasonal cycle appears strongest at 35°S with maxima centered in winter. Concentrations within 10 km of shore are > 2.0 mg m^{-3} in most months but extend farthest offshore (30 km) in May, June, and August (late fall, winter). Concentrations > 1.0 mg m^{-3} extend over 40 km offshore from May through September, extending over 120 km offshore in May. At 40°S, the data show that increased nearshore concentrations begin earlier in the calendar year (fall) than those at 35°S. Concentrations > 1.0 mg m^{-3} extend between 40 and 50 km offshore from March through May, reaching a maximum cross-shelf distance of 70 km in July. Concentrations > 2.0 mg m^{-3} are present within the 10 km closest to the coast in all months except spring (October - December) and February, suggesting a fall - winter maximum. The most persistent onshore penetration of oligotrophic conditions (<0.25 mg m^{-3}) is in summer (December - February). A seasonal cycle in 1979 is less evident in the data from 45°S; however, concentrations nearshore have a pattern consistent with the seasonal cycle at 40°S. Maximum cross-shelf extension of concentrations > 2.0 mg m^{-3} is present in fall – winter (April, May and July).

The data from 1981 (Figure 3) do not allow visualization of a complete seasonal cycle at any of the study latitudes. Those data that are available, however, show that pigment concentrations are generally higher in 1981 than 1979 and that highest coastal concentrations and the largest offshore extensions of high concentration are generally present in austral winter. At each latitude, maximum concentrations and maximum cross-shelf extensions are evident in winter (July or July-August (35°S)). Missing data at 45° prevent any interpretation of a seasonal pattern. Cross-shelf patterns in 1983 (Figure 4) are also incomplete because of missing data. Those data that are available, however, are consistent with the patterns of 1979 and 1981. The available data show a fall-winter concentration maximum within 50 km of the coast and in cross-shelf extensions of elevated pigment concentrations. These data also show that at the lower latitudes (20° - 30°S), nearshore concentrations are lowest and elevated pigment concentrations have the least cross-shelf extension.

3.3. Latitudinal Variability

The seasonal cycle of satellite-measured pigment concentration as a function of latitude in 1979 (the only year with data in each month) is shown in Figure 5 for the ~10 km immediately adjacent to the coast and a ~10 km wide region beginning 50 km offshore. A strong discontinuity is present at approximately 33°S in the region nearest shore (Figure 5a) in both absolute pigment concentrations and the strength of the seasonal cycle. South of this, concentrations are higher (> 1.5 mg m^{-3} over most of the year) than those to the north, and the seasonal cycle is relatively strong. This discontinuity is strongest in fall-winter and weakest in summer. The seasonal cycles in both the coastal region and the region 50 km offshore (Figure 5b) are in phase, with maximum concentrations in austral fall-winter (April-August). Coastal pigment concentrations > 2.0 mg m^{-3} are sustained throughout the year between 36° and 39°S, the same latitude at which offshore concentrations reach their seasonal maximum. North of 33°S, the seasonal cycle is considerably weaker. In the region closest to the coast (Figure 5a), mean monthly pigment concentrations rarely exceed 1.5 mg m^{-3}. Between 33° and 23°S, the data suggest two maxima, one in austral fall (May-June, in phase with the seasonal cycle at higher latitudes) and another in summer (December-February). At the lowest latitudes of the study area (< 23°S), the seasonal cycle is weaker still, with minimum concentrations in summer (January-February). Fifty kilometers offshore (Figure 5b),

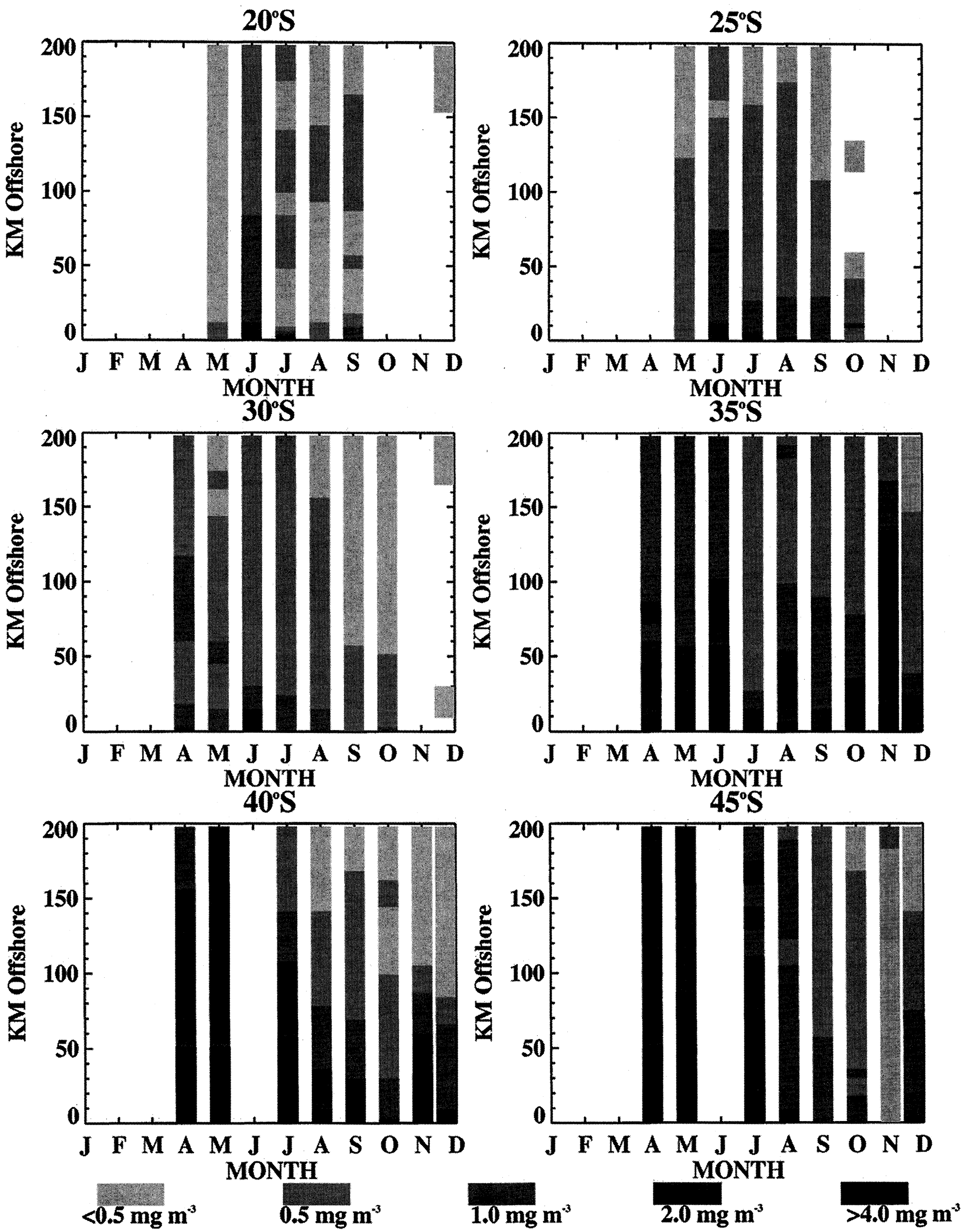

Figure 4. The seasonal cycle of cross-shelf phytoplankton pigment distribution at six latitudes within the study area for 1983 (as in Figure 2). Note that concentration bins are different from those of 1979.

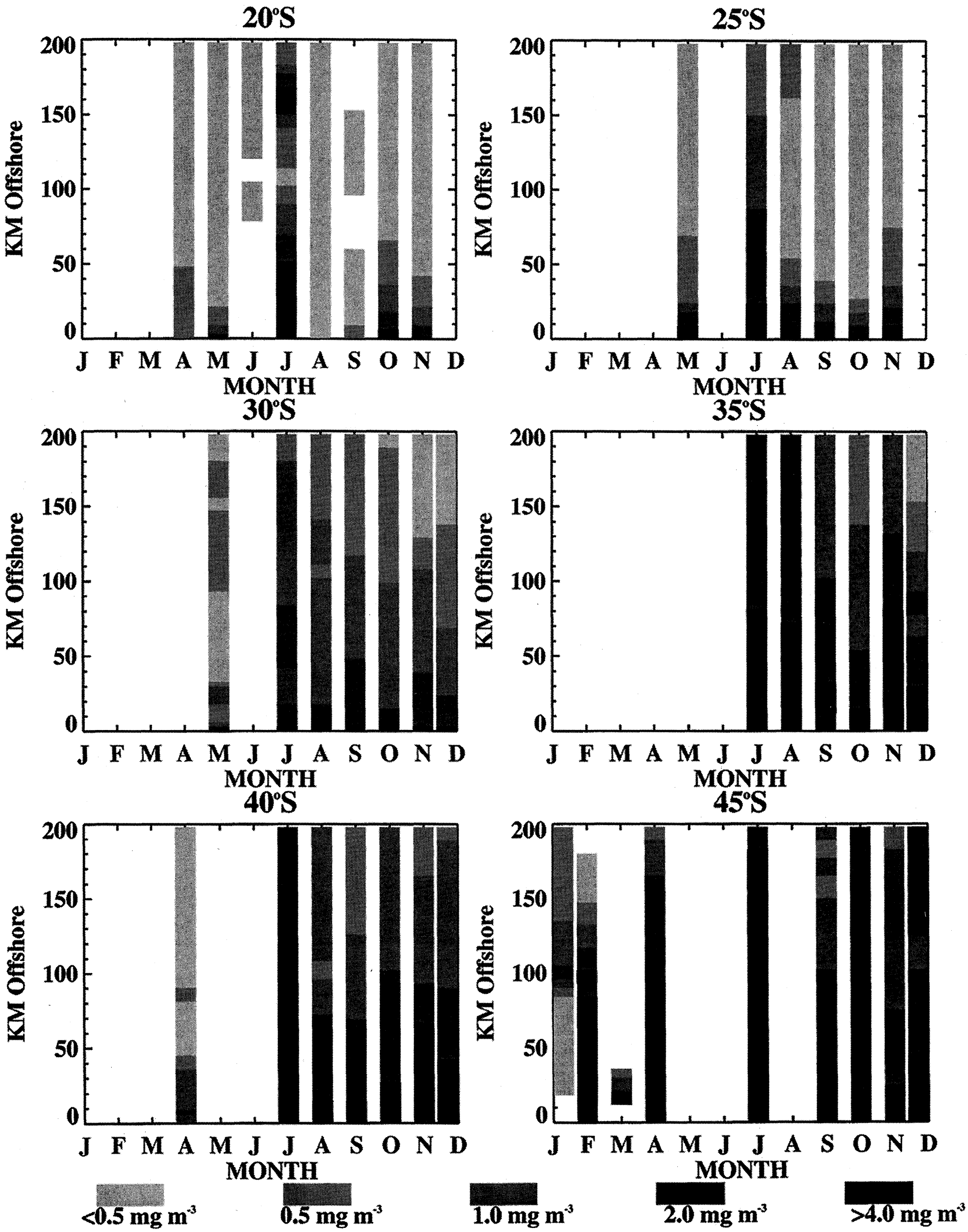

Figure 3. The seasonal cycle of cross-shelf phytoplankton pigment distribution at six latitudes within the study area for 1981 (as in Figure 2). Note that concentration bins are different from those of 1979.

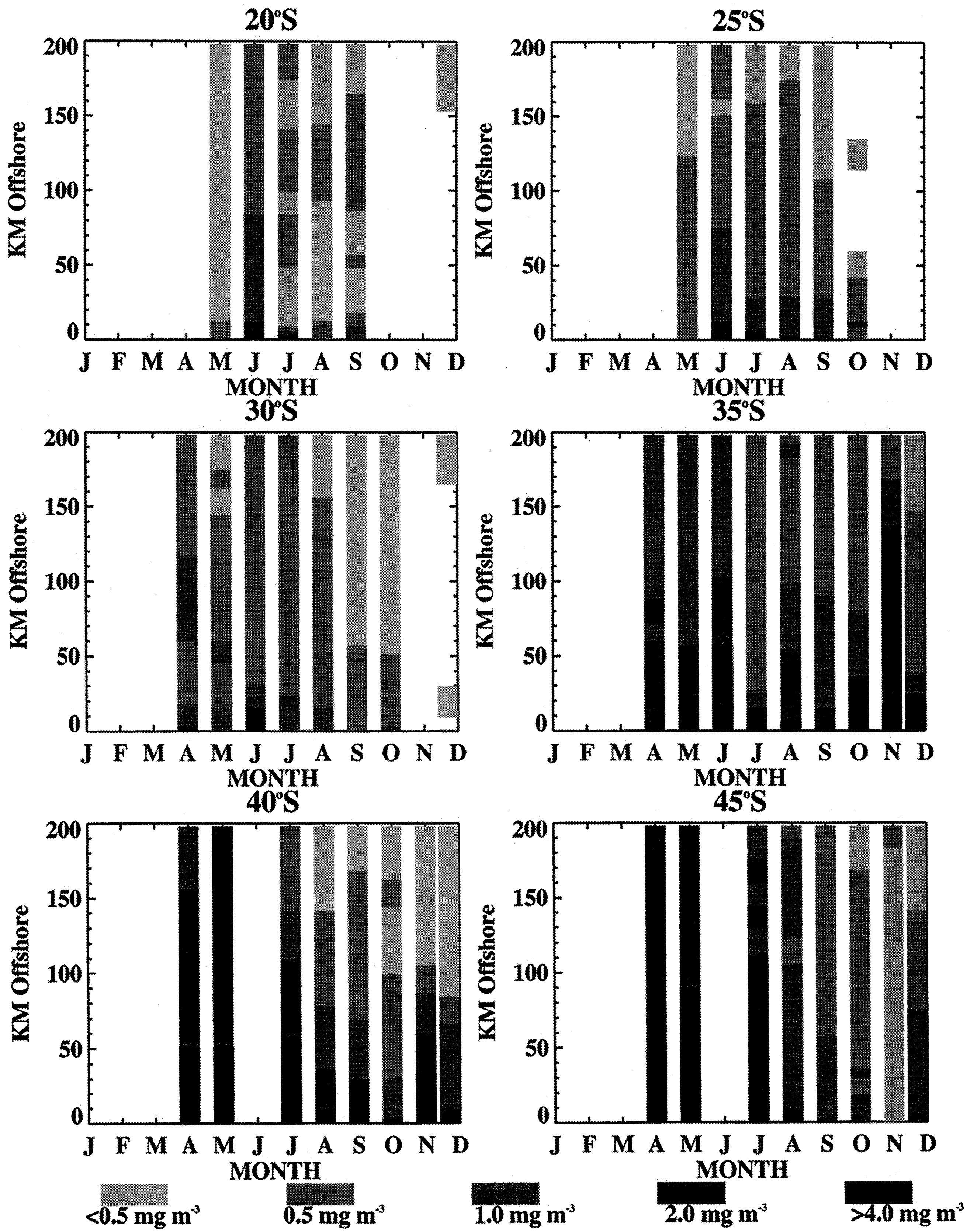

Figure 4. The seasonal cycle of cross-shelf phytoplankton pigment distribution at six latitudes within the study area for 1983 (as in Figure 2). Note that concentration bins are different from those of 1979.

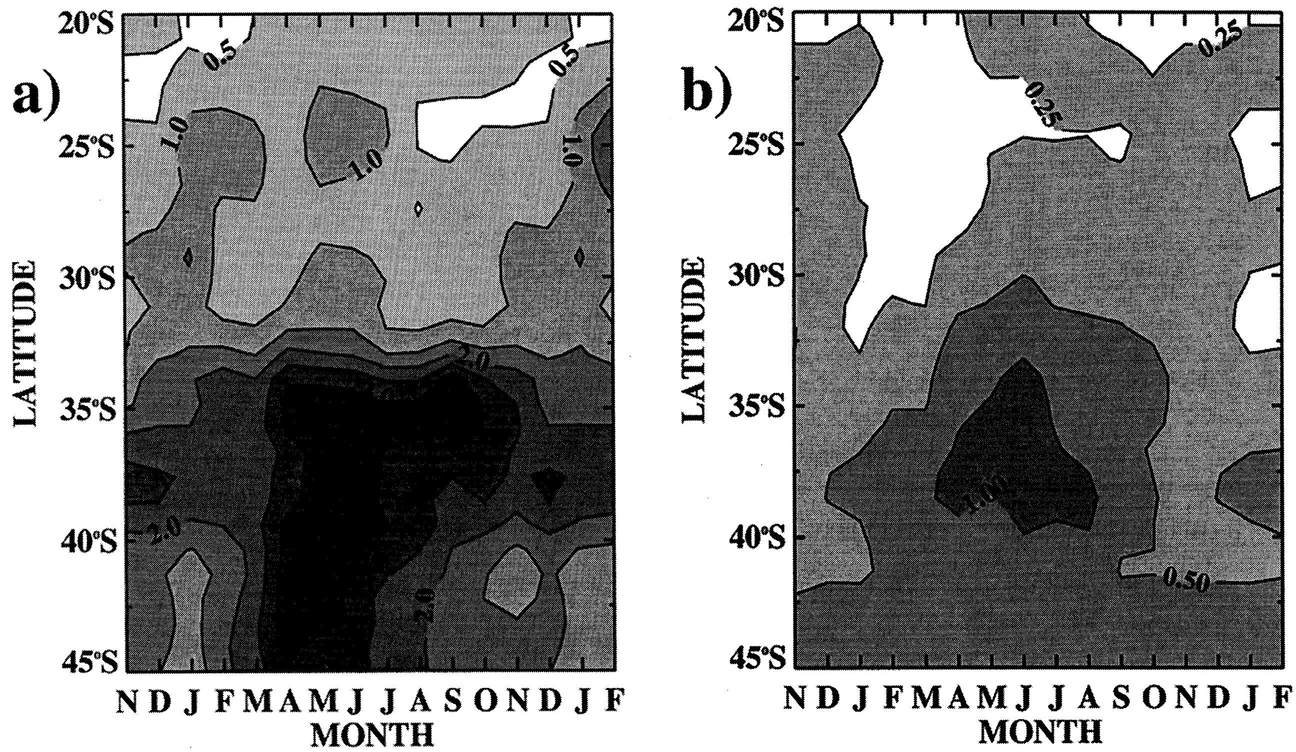

Figure 5. The seasonal cycle of satellite-measured phytoplankton pigment distribution in 1979 along the latitudinal extent of the study area averaged at each pixel (4 km) of latitude over (a) a ~10 km wide region adjacent to the shore and (b) a ~10 km wide region centered 50 km offshore. Pigment concentrations in mg m^{-3} are shown as contours in time and latitude.

patterns between 33° and 23°S indicate a weak seasonal cycle with a maximum in winter - spring (July - December) and minimum concentrations in summer - fall (January - April), out of phase with the seasonal cycle closer to shore.

The same latitudinal profiles were calculated from climatological monthly images calculated by compositing calendar months from all 5 years of data (1979-1983). These data (Figures 6a and 6b) show that despite bias introduced by both missing data in the years 1980-1983 and interannual variability, most of the seasonal - latitudinal patterns evident in 1979 are maintained. Climatological concentrations in both the coastal and offshore region are higher than those present in 1979. The latitudinal discontinuity at approximately 33°S is evident both nearshore and 50 km offshore. South of this latitude, concentrations are > 3.0 mg m^{-3} from April through December, with a minimum in austral summer. The summer minimum extends to include both spring and summer at the highest latitudes of the study area (> 42°S). The seasonal cycle is the same 50 km offshore. At latitudes north of 33°S, the seasonal cycle is stronger than that evident in 1979 but biased by missing data. A single winter maximum and summer minimum are present both within 10 km of the coast and 50 km offshore. The climatological CZCS data therefore suggest that the coastal seasonal cycle is in phase throughout the latitudinal range of the study area.

3.4. Wind Forcing

The seasonal cycle of alongshore wind stress over the study area is shown in Figure 7. Alongshore wind stress over the Chilean coast has a latitudinally dependent seasonal cycle [*Bakun and Nelson*, 1991; *Thomas et al.*, 1994]. As is characteristic of all eastern boundary current regions [*Hill et al.*, 1998], climatological wind forcing (Figure 7a) at higher latitudes has a winter reversal to downwelling favorable winds. This reversal extends north to 32.5°S, with a temporal persistence that increases with increasing latitude such that at 45°S, monthly mean upwelling favorable winds are restricted to late spring and summer months (December – February). At lowest latitudes, winds are weaker but upwelling-favorable throughout the year. Strongest upwelling-favorable winds are present in summer at midlatitudes, between 27°S and 41°S, a pattern analogous to that off central California [*Strub et al.*, 1990]. These ECMWF data indicate considerable interannual variability. The seasonal cycles of wind forcing for the three most complete years of CZCS coverage (1979, 1981, 1983) are shown in Figures 7b, 7c, and 7d. Of these, 1979 appears most similar to the climatology, with relatively weak upwelling winds in summer. In both 1981 and 1983, summer upwelling is stronger than in 1979, and downwelling-favorable winds in winter months extended to latitudes lower than 32.5°S. In 1983, the ECMWF data indicate all latitudes experienced a winter shift to mean downwelling conditions.

4. Discussion

Patterns of pigment evident in the "individual" scenes (Plate 1) demonstrate the existence of eddies and filaments of elevated phytoplankton pigment extending offshore in the Chilean upwelling region. These data indicate that patterns identified by *Uribe and Neshyba* [1983] and *Espinoza et al.* [1983] are recurring features in both time and space. In the

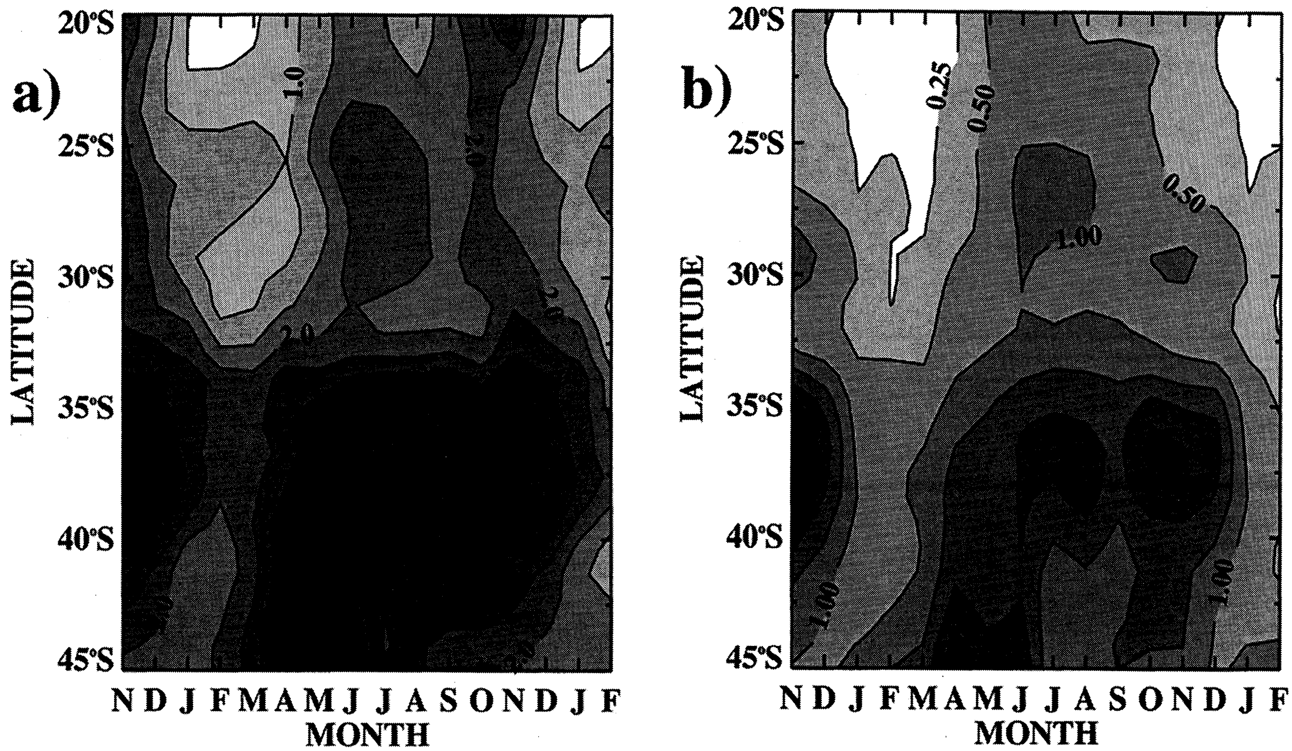

Figure 6. The climatological (1979-1983) seasonal cycle of satellite-measured phytoplankton pigment distribution along the latitudinal extent of the study area for (a) a ~10 km wide region adjacent to the shore and (b) a ~10 km wide region centered 50 km offshore. Pigment concentrations in mg m^{-3} are shown as contours in time and latitude.

California Current, pigment distributions are closely coupled with SST patterns [*Abbott and Zion*, 1985; *Strub et al.*, 1991]. The pigment filaments shown here are qualitatively consistent with previously published patterns of satellite-measured SST in the Chilean upwelling region. Along the northern coast (19° – 23°S), images shown by *Barbieri et al.* [1995] indicate colder coastal water resulting from upwelling is restricted to within 10 - 30 km with isolated filaments extending up to 150 km offshore. Images presented by *Yáñez et al.* [1996a, b] show the surface temperature front in the region between 32° and 35°S is approximately 50-100 km offshore. These authors show cold filaments extending beyond the western edge of their images (approximately 200 km offshore). The pigment filaments shown here are therefore similar in nature to those of surface temperature, a not unexpected result. However, this has not previously been demonstrated and is a necessary first step in using merged surface temperature and ocean color satellite data to examine variability in this upwelling system.

The latitudinal analysis of seasonal variability (Figures 5 and 6) indicates a spatial discontinuity at approximately 33°S, effectively dividing the Chilean upwelling region into two regimes. At higher latitudes, concentrations are relatively high throughout the year, and the seasonal cycle is relatively strong and extends offshore to at least 50 km. North of 33°S, near-coast pigment concentrations are lower, and the seasonal cycle is weaker and less well connected to that 50 km offshore. This latitudinal pattern has some parallels with that of alongshore wind forcing (Figure 7a and reviewed by *Strub et al.* [1998]). North of approximately 33°S, winds are upwelling favorable throughout the year and become progressively weaker with decreasing latitude. South of this, wind forcing shifts seasonally from mean upwelling to mean downwelling-favorable conditions. *Strub et al.* [1998] review evidence that during summer this latitude may also be a hydrographic boundary. First, it may be the northern limit of a tongue of low-salinity surface water originating at higher latitudes and the southern limit of higher-salinity subtropical water, and, second, an equatorward flowing jet may be farther offshore south of this approximate latitude, intruding closer to shore north of this. Each of these may impose direct or indirect influence on large-scale biological patterns, discussed further below.

Over most of the latitudinal range of the Chilean coast examined here, *Thomas et al.* [1994] show that the seasonal cycle of pigment concentration appears either uncoupled from seasonal variability in wind forcing or is not resolved. *Strub et al.* [1990] show that offshore regions of the California Current (100-300 km offshore, maximum in spring) are also out of phase with alongshore wind stress and the pigment seasonal cycle closer to shore (0-25 km offshore, maximum in summer). The possibility therefore existed that the 100 km cross-shelf means of *Thomas et al.* [1994] more closely represent an offshore signal, out of phase with local forcing and coastal conditions, especially in areas with a very narrow upwelling region [*Morales et al.*, 1996]. Pigment concentrations analyzed here to resolve patterns closer to shore demonstrate that the 100 km spatial means of *Thomas et al.* [1994] are qualitatively similar to patterns within ~10 km of the coast and 50 km offshore (Figures 2 - 6). Both are 180° out of phase with seasonal maximum in alongshore wind

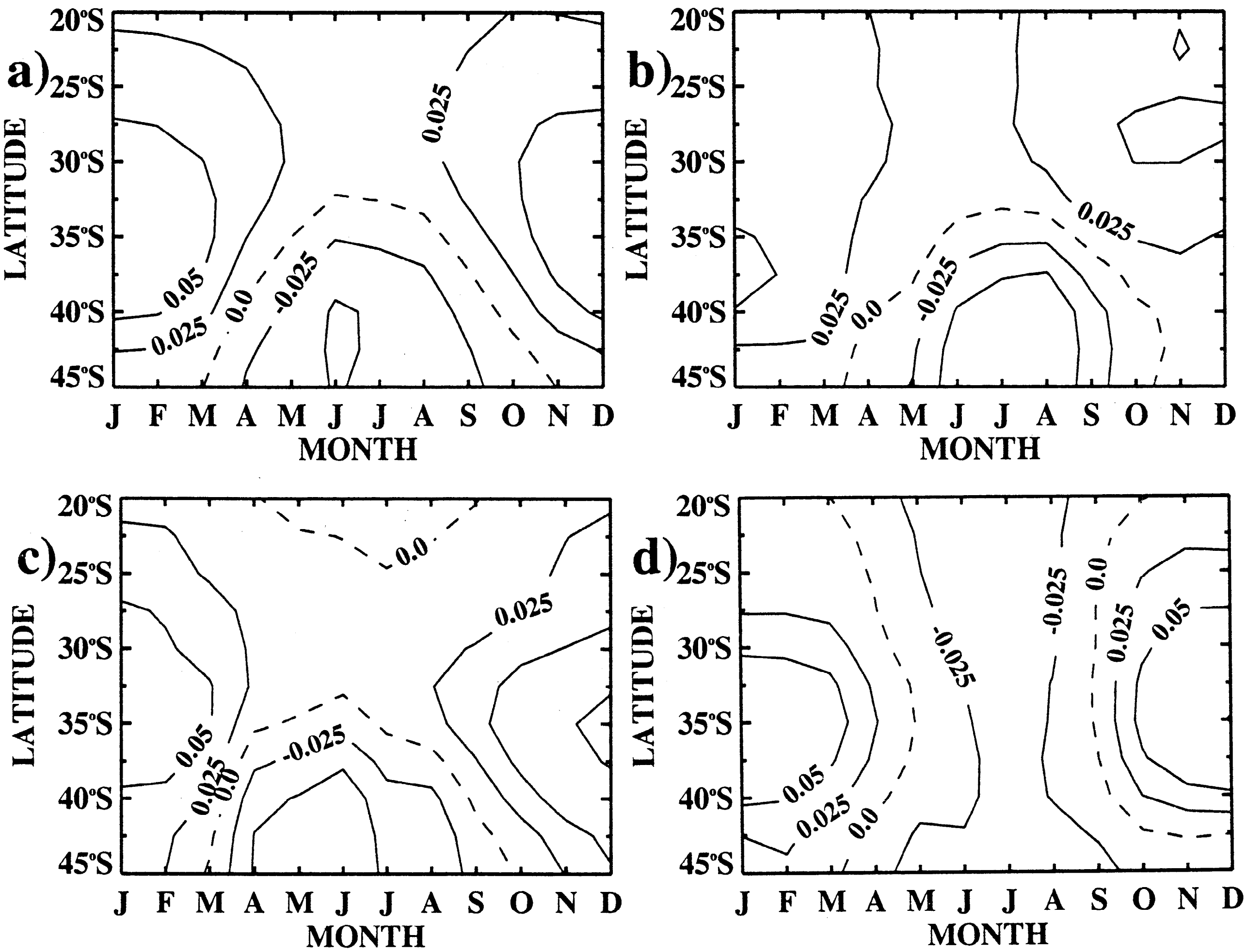

Figure 7. The seasonal cycle of alongshore wind stress (dynes cm^{-2}) as a function of latitude over the study area, calculated from ECMWF data showing (a) a 10 year climatology (1979-1988) (b) 1979, (c) 1981, and (d) 1983. Positive values are equatorward (upwelling favorable).

stress (Figure 7). Along the northern Chilean coast (18° – 25°S), seasonal variability close to the coast is evident (Figures 2 - 6) that was not well resolved by *Thomas et al.* [1994]. Furthermore, patterns within individual years presented here (Figures 2-4) suggest that although actual concentrations exhibit strong interannual variability, to the extent visible between missing data gaps, the seasonal cycles measured by the CZCS are consistent from year to year.

An obvious question is whether sea surface temperature patterns have a seasonal cycle similar to either the pigment or wind patterns. Seasonal cycles of cross-shelf SST profiles at six latitudes through the study region are constructed from the climatological monthly Pathfinder SST image sequence. The 20 km spatial resolution of these data prevents a detailed examination of the region closest to the coast. The seasonal cycle of SST is dominated by the annual cycle of solar heating [*Barbieri et al.*, 1995], which acts to mask any coastal SST signal resulting from wind-driven upwelling. Assuming that seasonal solar heating is the same at locations of equal latitude, the difference between the coastal SST and an SST offshore, away from the eastern boundary current regime at the same latitude, in each month will produce a measure of coastal SST "deficit," reducing the effect of seasonal solar heating. Seasonal cycles of coastal deficit, defined here as the difference between temperatures within 200 km of the coast and those 400 km offshore at the same latitude, at six latitudes, are shown in Figure 8. Magnitudes of the coastal deficits are maximum at midlatitudes, spatially coincident with maximum wind forcing. At higher latitudes (35°, 40°, and 45°S) and also at the lowest latitude (20°S), coastal SST deficit is maximum in summer – early fall and minimum in winter – spring, lagging behind the climatological maximum in upwelling favorable wind stress by 1 – 2 months (Figure 7a). At these latitudes, then, the seasonal coastal deficit is negatively correlated with the seasonal cycle of pigment (Figures 5 and 6). At 25°S and 30°S the seasonal cycle of SST deficit is maximum in late fall – winter, out of phase with upwelling favorable wind but coincident with the seasonal maximum in pigment concentration. Reasons for this difference are unclear; however, the coastal deficit metric of upwelling does not take into account advection and other processes which may influence the zonal SST gradient. A separate analysis of coastal SST deficit carried out on the northern Chilean coast (north of 24°S) using 1 km resolution images from 1996 (A.C. Thomas et al., manuscript in preparation, 1999) shows maximum deficit in summer, in

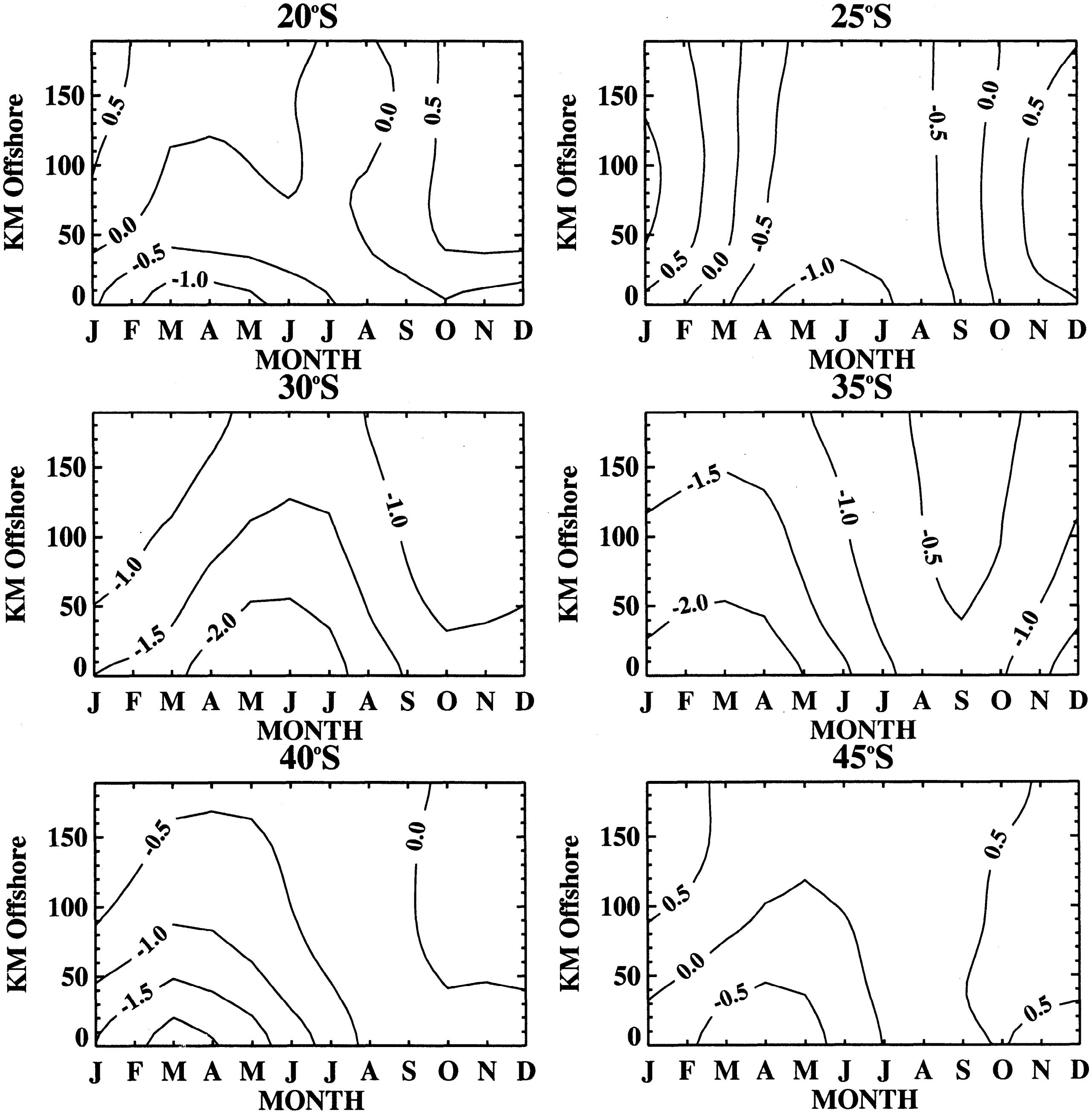

Figure 8. The seasonal cycle of coastal surface temperature deficit as a function of cross-shelf distance and month at each of six latitudes within the study area. Deficits were calculated from Pathfinder advanced very high resolution radiometer data composited over the period 1987 - 1993. Negative values indicate colder sea surface temperatures than those 400 km offshore.

phase with seasonal wind forcing and consistent with the analysis at 20°S shown here (Figure 8). Except at 25° and 30°S, the SST metric of upwelling used here appears consistent with the seasonal cycle of upwelling-favorable wind forcing, but neither is consistent with the view that increased upwelling results in increased phytoplankton pigment concentrations near the coast.

Explanations for the observed differences in seasonal cycles are not obvious in these data. We cannot discount the possibility that errors in CZCS-estimated concentrations result in an inaccurate seasonal cycle. *Chavez* [1995] has shown that the climatological cross-shelf profile of CZCS pigment concentrations off Peru is less than that created from in situ data. This discrepancy may be a result of inaccurate atmospheric correction or characteristics of the optical properties of the phytoplankton community present. A number of possibilities exist which might explain the apparent decoupling of the pigment concentration seasonal cycles and those of alongshore wind stress. *Strub et al.* [1995] show that an offshore (100-300 km) poleward current evident in altimeter data is also not in phase with local winds, suggesting a possible role for large-scale advective processes. Biological

/ physical coupling might play a role. The time/space variability of primary production in the Chilean coastal zone may be such that the monthly means calculated here do not resolve patterns and response in this system adequately. *Carr* [1998] uses a biological model to show that differences in the episodic nature of wind forcing can induce significant differences in carbon flux through trophic levels and phytoplankton biomass. Previous authors have pointed to differences in the biological pathways and hence productivity efficiency [*Lluch-Belda et al.*, 1989; *Hutchings*, 1992] between different upwelling systems. Higher efficiency in this eastern boundary current is explained by a shorter food chain [*Cushing*, 1989]. Higher biological efficiency under similar physical upwelling conditions might result in a weaker coupling between the patterns of SST and pigment than those evident off California [*Denman and Abbott*, 1994; *Abbott and Letelier*, 1998]. This can now be tested with concurrent ocean color and surface temperature imagery during the SeaWiFS era. Coastal-trapped waves might be a significant source of variability along the northern Chilean coast [*Shaffer et al.*, 1997] at temporal frequencies not resolved by the CZCS data. *Shaffer et al.* [1997] suggest that such forcing might interact with local alongshore wind stress to enhance or suppress the biological consequences of upwelling. Eastward flow at 100 m measured by coastal current meters might bring offshore oligotrophic water into the coastal zone, restricting the offshore extent of pigment created during upwelling events [*Shaffer et al.*, 1995]. The continental shelf is relatively narrow off Chile. This, coupled with differences in the cross-shelf position of coastal currents [*Fonseca*, 1989; *Strub et al.*, 1995] and differences in the interaction of the eastern boundary current regimes with basin-scale flows (West Wind Drift and the California Current analogue, the North Pacific Current), leads to differences in connections between coastal upwelled water and open ocean water. In the California Current, the offshore extent of the high-pigment patterns appears constrained by the main current jet [*Strub et al.*, 1991]. If this is also true off Chile, coastal current structure may be responsible for differences [*Strub et al.*, 1998]. Large-scale oceanic forcing, uncoupled from local wind forcing, might therefore play a role in determining the coastal seasonal pigment patterns presented here. *Strub et al.* [1990] show that even in a data set with significantly fewer missing data points (the California Current region), statistical relationships between satellite pigment and wind forcing are relatively weak. Extensive missing data within the pigment time series here (Figures 2-4 and *Thomas et al.* [1994]) might provide a biased view of seasonal patterns, preventing realistic relationship from being evident. Especially at lower latitudes in austral summer, missing data prevent a consistent view and provide a strongly biased climatology, emphasizing the need, in this data set, for examining individual years.

5. Summary

CZCS image composites of phytoplankton pigment concentration along the Chilean coast over short time periods (2-4 days) show that filaments of elevated pigment concentration, originating at the coast in upwelling regions, extend offshore over distances of over 300 km, qualitatively similar in appearance to previously published descriptions of temperature filaments and to pigment filaments off California. A quantitative and statistical analysis of these filaments is not possible because of missing data.

To the extent that coverage in each of the years allows, the annual cycle appears qualitatively similar, with a maximum in pigment concentrations in austral winter. At the lowest latitudes (20° and 25°S), this variability occurs within 25 km of the coast. At higher latitudes, this pattern is evident from 50 to 100 km offshore. There is evidence of considerable interannual variability in pigment concentrations between 1979, 1981, and 1983, the only years for which sufficient data exist for a partial glimpse at the seasonal cycle. Concentrations are lowest at all latitudes in 1979 and higher by approximately a factor of 2 in 1981 and 1983.

Latitudinal examination of the annual cycle indicates a discontinuity at approximately 33°S. At higher latitudes, pigment concentrations are higher, and the seasonal cycle is both strong and well correlated with that 50 km offshore. At lower latitudes, concentrations are consistently lower, and the seasonal cycle is weaker. The strength of this discontinuity is maximum in fall-winter. The data show that maximum cross-shelf extension of elevated pigments and maximum coastal concentrations occur centered on austral winter (June – September), with minimum concentrations centered on summer. This is 180° out of phase with the seasonal cycle of upwelling favorable alongshore wind stress. Analysis of climatological satellite SST shows that the seasonal cycle of relatively cold coastal temperature lags behind that of wind stress by 1-2 months and is also out of phase with the pigment seasonal cycle. Only at midlatitudes (25 ° and 30°S) is the metric of upwelling calculated here (coastal SST deficit) in phase with maximum pigment concentrations.

Despite the incomplete time series, available CZCS data are sufficient to provide examples of spatial aspects of large-scale pigment variability and can provide at least preliminary answers to the posed questions. A full year of SeaWiFS data covering the Chilean upwelling region is now available and is being analyzed. The large anomalies in this first year of data, however, associated with the extreme 1997-1998 El Niño, prevent a meaningful direct comparison. These data will be presented separately as an analysis of El Niño conditions (A.C. Thomas et al., manuscript in preparation, 1999) A more complete analysis of chlorophyll patterns in the Chilean coastal zone awaits the development of a more extensive SeaWiFS time series in conjunction with concurrent in situ ocean color calibration data.

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