12-2002

Satellite-Measured Chlorophyll Variability Within the Upwelling Zone Near Heceta Bank, Oregon

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SATELLITE-MEASURED CHLOROPHYLL VARIABILITY WITHIN THE UPWELLING ZONE NEAR HECETA BANK, OREGON

By

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B.S. Rutgers University, 2000

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Oceanography)

The Graduate School

The University of Maine

December, 2002

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Thesis Advisor: Dr. Andrew Thomas

An Abstract of the Thesis Presented
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Heceta Bank, a unique shallow bank on the southern Oregon shelf, is located within the California Current upwelling system. Four years (1998-2001) of 1-km resolution SeaWiFS ocean color satellite data of the Oregon coast are used to provide the first systematic description, and quantification of seasonal and interannual surface chlorophyll variability in the Heceta Bank region of coastal Oregon. The variability over the bank is examined with respect to wind forcing and surface temperature, and compared to the variability observed in topographically simpler shelf regions north and south of the bank.

A seasonal cycle with lowest concentrations in the fall and winter (October-April), an increase in the spring and early summer (May-July) and maxima in the summer (July-August) is evident along the entire Oregon coast. A spatial pattern of elevated chlorophyll values nearshore and lower values offshore dominates during the summer months. The pattern is enhanced in strength and cross-shelf extent over Heceta Bank and is appears to mimic shelf bathymetry. The chlorophyll pattern, as well as the seasonal

pattern of SST, is consistent with latitudinal gradients of local wind forcing in the area. Interannual differences over the study period show the magnitude of this pattern to be strongest in 2001 and weakest in 1999. Cross-shelf maximum extension of chlorophyll occurred later in the summer season during the 1997-98 El Nino year on Heceta Bank and north of the bank. South of the bank, wind forcing may have been strong enough to overcome the warmer spring temperatures attributed to El Nino to begin the seasonal elevation of chlorophyll in April.

Temporal variability on 8-day time scales of chlorophyll concentrations on Heceta Bank are positively correlated with areas immediately north and south of the bank, however, the correlation between locations becomes insignificant when the distance exceeds 1° of latitude. Comparison of chlorophyll variability over Heceta Bank with those of adjacent shelf regions (north and south of the bank) at similar depths were contrasted with variability at similar cross-shelf distances to examine the effect of a wider shelf on chlorophyll concentrations. Although at similar depths specific differences between sites are evident on the shelf, these differences are not consistent from year to year and chlorophyll variability north and south of the bank is similar to that on Heceta Bank. At an equal distance from shore however, the northern and southern sites have consistently weaker chlorophyll concentrations than those over Heceta Bank suggesting that shelf width exerts a strong control on the cross-shelf extent of chlorophyll off the Oregon coast. Cross-shelf extensions of chlorophyll > 4 mg m^{-3} over Heceta Bank is confined to the shelf (55 km) in the summer months. North and south of the bank, where the shelf is relatively narrow, chlorophyll > 4 mg m^{-3} extend up to 35 km from the coast,

20 km beyond the shelf break. The wider shelf over Heceta Bank results in elevated chlorophyll concentrations farther offshore than adjacent shelf regions.

ACKNOWLEDGEMENTS

I would like to thank P. Ted Strub, Francois Baratange and Jack Barth of Oregon State University for their assistance in this project. Dr. Strub granted me access to his AVHRR SST database. Mr. Baratange processed the SeaWiFS data of the Oregon coast and made it possible for me to obtain it off OSU servers. Dr. Barth supplied me with a 5 km bathymetric dataset of the Oregon coast.

I would also like to extend a special thanks to Ryan Weatherbee and Remy Luerssen for their professional and personal friendship, Peter Brickley for his physical oceanographic wisdom and candid advice, Brandon Sackmann and Kasey Leggard for their feedback on this project, my committee members, Mary Jane Perry and Lee Karp-Boss for their feedback and advice, and Andy Thomas for his patience and guidance through this project. Finally I would like to thank my family and all of my treasured friends in this world. I would be lost without them.

Support for this project was provided under NASA grants NAG5-6558 and NAG5-6604 and NSF grants OCE-9711919 and OCE-0000899.

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Chapter 1

INTRODUCTION

The Oregon coast (Figure 1.1) is part of the California Current System (CCS), an eastern boundary current upwelling system noted for its high biological productivity and complex physical oceanography [*Hickey*, 1998]. At higher latitudes within the CCS, the strong seasonal cycle of winds is controlled by large-scale atmospheric pressure systems that shift the dominant alongshore wind direction from poleward in the winter to equatorward in the summer [*Huyer*, 1983]. This system imposes a strong seasonality on current structure, sea surface temperature (SST) and surface chlorophyll patterns. The northerly winds drive an offshore Ekman transport resulting in coastal upwelling. During the summer upwelling season, coastal features (such as capes or coves) and bottom topography play a key roll in the development of eddies, squirts and cold core filaments of chlorophyll enriched waters [*Hill et al.*, 1998; *Ikeda and Emery*, 1984]. These features extend more than 300 km offshore and are often observed in satellite images of areas south of Cape Blanco (Figure 1.1) [*Strub et al.*, 1991; *Abbott and Barksdale*, 1991; *Abbott and Zion*, 1987; *Pelaez and McGowan*, 1986; *Abbott and Zion*, 1985; *Flament et al.*, 1985; *Kelly*, 1985; *Ikeda and Emery*, 1984]. The coast of Oregon north of Cape Blanco is characterized by a relatively straight coastline and narrow shelf with a spatially uniform, seasonal pattern of upwelling in the summer months [*Hickey*, 1998; *Landry et al.*, 1989; *Strub et al.*, 1990]. Here, the cross-shelf spatial pattern of surface chlorophyll concentrations and SST are generally parallel to the coast. The one topographic feature that interrupts this uniformity is Heceta Bank.

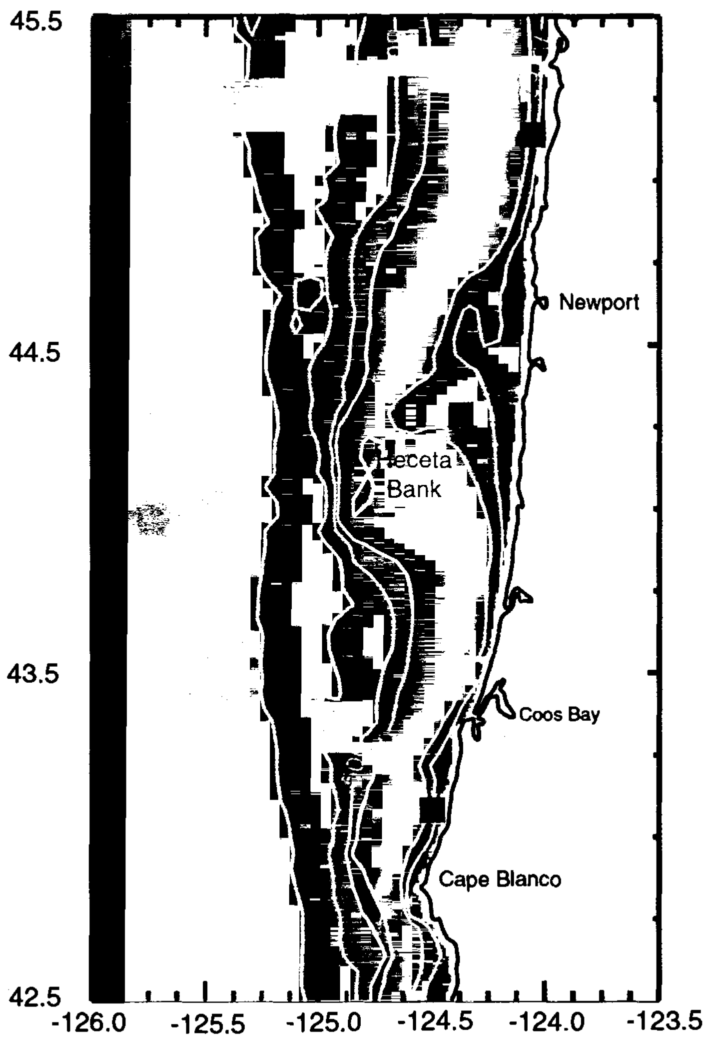

Figure 1.1 - *Map of Study Region*
4-year climatological composite of SeaWiFS 1km chlorophyll data, with bathymetric contours overlaid, showing the location of Heceta Bank and the three study locations discussed in this study.

The Oregon coast stretches between 42°N and 46°N spanning approximately 483 km of coastline. Heceta Bank is off the southern Oregon coast on the continental shelf about 55 km offshore at 44°N, 125°W rising up from depths of over 1,000 m to <50 m (Figure 1.1). Shallow banks such as Heceta Bank often provide a unique habitat for marine flora and fauna. Local fishing success on the bank is a good indication that mixing of upwelled water and primary productivity are probably enhanced near the bank [*Hickey*, 1998]. Trawlable areas on the bank support a large portion of Oregon's commercial fishery [*Pearcy et al.*, 1989]. Differences in circulation over the bank may have a dramatic effect on the transport and/or retention of phytoplankton, zooplankton and fish. Heceta Bank may disrupt the along- and cross-shelf spatial pattern of response by phytoplankton to upwelling events. Meanders of the coastal jet that lead to cold core filaments are believed to originate just south of the bank [*Hickey*, 1998; *Strub et al.*, 1990]. A systematic examination of the patterns of surface chlorophyll in the vicinity of Heceta Bank has not been published.

To date, greater attention has been given to the satellite oceanography of areas south of Oregon, within the California Current, where the coastline orientation and bathymetry are more variable, and surface patterns resulting from upwelling are correspondingly more variable than those off the Oregon coast. *Pelaez and McGowan* [1986] observed in Coastal Zone Color Scanner (CZCS) imagery elevated pigment structure overlying ridges and banks off the coast of California. They also found surface chlorophyll patterns in both time and space that corresponded well with coincident satellite derived SST. Using *in situ* surface temperature and CZCS chlorophyll data *Abbott and Zion* [1985] found evidence of a temporal lag between changes in temperature

and the subsequent biological response. Intermediate temperatures [10-14°C] were found to have the highest chlorophyll concentrations. *Abbott and Zion* [1985] suggested that the coldest temperatures with low chlorophyll concentrations represent freshly upwelled water where phytoplankton have yet to respond to the increased nutrients. Water warmer than the optimal range [10-14°C] is previously upwelled water where the phytoplankton concentrations have already peaked and the community is now suffering from nutrient limitation. This senario is consistent with the physiological picture of upwelling and phytoplankton response given by *Mac Isaac et al.* [1985]. *Denman and Abbott* [1988] determined that the temporal decorrelation scale of satellite-measured pigment patterns (CZCS data) at spatial scales of 25-50 km off Vancouver Island, Canada is on the order of 2-5 days. Building on this work, *Denman and Abbott* [1994] concluded that SST and phytoplankton pigment patterns are correlated at zero temporal lag off northern California suggesting that in coastal upwelling regimes the spatial distribution of phytoplankton is largely controlled by physical forcing.

Previous work based on *in situ* data documents details of specific physical and biological dynamics off the Oregon coast [e.g. *Hill*, 1998; *Hickey*, 1998; *Lentz*, 1992; *Landry et al.*, 1989; *Hickey*, 1989; *Huyer*, 1977]. Relatively few studies use satellite ocean color data to quantify the spatial and temporal variability of chlorophyll in this area on scales sufficient to resolve the details on the shelf. The region is often cloudy and data from CZCS were relatively sparse. In addition, the CZCS atmospheric correction algorithm produced artificially high values of pigment concentration at large solar zenith angles (higher latitudes during winter months) [*Thomas and Strub*, 1989].

Previous examinations of satellite ocean color data in the CCS have studied larger scale patterns or processes in the CCS but include the Oregon coast as a sub-region. *Strub et al.* [1990] showed the seasonal increase in pigment concentration to peak first off northern California (35-42°N) in late-spring and move north to Oregon (42-46°N) by mid-summer. The lack of a spring bloom observed by *Landry et al.* [1989], using *in situ* data, was supported by the satellite observations made by *Strub et al.* [1990]. *Thomas and Strub* [1989] however, showed a large degree of interannual variability in CZCS pigment distributions during the spring transition, resulting in a spring bloom off Oregon in some years. Both *Thomas and Strub* [1989] and *Strub et al.* [1990] showed that alongshore wind stress and wind induced vertical mixing play a role in chlorophyll temporal patterns in the CCS. *Thomas and Strub* [2001] showed that correlations between alongshore wind stress and cross-shelf CZCS pigment structure off Washington and Oregon were poor. They concluded that although cross-shelf pigment patterns at the 50-100 km scale in this region may respond to overall wind strength over a 10-20 day time scale, these patterns are poorly related to local alongshore winds. *Thomas and Strub* [2001] also described two seasonal offshore expansions of chlorophyll occurring in the spring (April-May) and summer (August) off Oregon and Washington. The maximum cross-shelf extension of elevated chlorophyll pigments in this region was 100 km offshore.

Many of the systematic analyses of multi-year time series of satellite ocean color data within the CCS make use of data sets gridded to a spatial resolution of 4-km or greater [e.g. *Thomas and Strub*, 1989; *Strub et al.*, 1990; *Thomas and Strub*, 2001; *Thomas et al.*, 2001]. These data provide adequate quantification of large-scale temporal and spatial patterns of chlorophyll. In these data, however, details of small-scale features

such as the circulation patterns off Heceta Bank and other coastal locations are poorly resolved. Using 1km resolution CZCS data of central California (30-40°N), *Abbott and Barksdale* [1991] described the coupling of wind forcing and seasonal patterns of coastal pigment distribution, showing that wind forcing, particularly wind stress curl, plays an important role in the distribution of phytoplankton pigments in that region. They also noted that changes in coastal topography might also play an important role in phytoplankton pigment distribution. With the launch of the SeaWiFS sensor in 1997, an operational 1-km ocean color product of the Oregon coast was made available, allowing a detailed analysis of the surface chlorophyll patterns in the Heceta Bank region.

The purpose of this paper is to examine the influence of a shallow bank on the seasonal, interannual and event scale variability of surface chlorophyll patterns in a coastal upwelling region. Specific goals are to provide the first systematic description, and quantification of seasonal and interannual surface chlorophyll variability in the Heceta Bank region of coastal Oregon, to compare this variability with that of surface temperature and wind forcing, and to contrast variability over the bank with that evident in topographically simpler shelf regions north and south of the bank. The large-scale seasonal trends described in previous analyses serve as a basis against which details examined at higher spatial resolutions here can be compared.

Chapter 2

DATA AND METHODS

Four years (1998-2001) of daily SeaWiFS satellite imagery were processed to chlorophyll concentrations (mg m^{-3}) at the Ocean Optics Laboratory at Oregon State University, using the OC4 version 3 algorithm with standard NASA global coefficients [*O'Reilly et al.*, 1998], to 1-km resolution images and remapped to a cylindrical mercator projection. On occasion, the satellite orbit configuration produces two scenes per day, one of which is invariably at a wide scan angle resulting in distorted pixels. These second images were removed from the dataset. Stray light occasionally results in erroneous chlorophyll values along the edges of clouds and land. To reduce this problem cloud and land pixels in the daily imagery were morphologically dilated by 1 pixel prior to all analyses. All available daily scenes within the study region were used to form a time series of temporal composites over 8-day and monthly periods. Monthly composites were then averaged over the 4 years to make a 12-month climatological time series.

Coincident NOAA AVHRR satellite images collected and processed to sea surface temperature (SST) and mapped to a rectangular grid at 1-km resolution by Ocean Imaging of Solana Beach, California, were obtained from the U.S. GLOBEC NE Pacific Satellite Data Archive. To reduce the effect of poorly masked cloud edges and land boundaries, these features were morphologically dilated by 2 pixels in all daily scenes prior to further analysis. All available scenes within single days were composited to form a time series of daily images. All available scenes were again used to form a time series of 8-day and monthly composites. To reduce error caused by poorly masked clouds, a

modified warmest-pixel approach was used that assumes poorly masked clouds would register as erroneously cold temperatures. Composites were formed by averaging the warmest 75% of valid data at each pixel location within the specified time frame (8-day or monthly). A climatological 12-month time series was produced by compositing each month from the four years together.

Monthly averages of wind-derived upwelling indices (offshore Ekman transport) for 1998 - 2001 were obtained from the NOAA Pacific Fisheries Environmental Laboratory.

Temporal variability of chlorophyll concentrations on Heceta Bank were examined by spatially averaging values within a 25 x 25 km box, centered over the bank (44.25°N, -124.38°W, 20-km from shore), extracted from the image time series. Comparison of chlorophyll variability over Heceta Bank with that of adjacent shelf regions at both similar depths (90-100 m) and similar cross-shelf distances (20-km from shore) were made by extracting similar 25 x 25 km regions from a southern site (43.17°N, -124.55°W) and a northern site (45.17°N, -124.14°W). Similar depth samples were taken only 10-km from shore at the northern and southern site because the shelf is very narrow at these locations. The northern location is south of the Columbia River (thereby reducing its influence) and north of where the shelf widens to form Heceta Bank. Cross-shelf variability was examined by extracting a swath (approximately 30-km wide in latitudinal distance), extending 150-km from the coast, from the image time series. Data within the month was then averaged in the along-shelf direction and smoothed by a 3x3 La Placian smoothing operator to fill in missing data. To place variability over Heceta Bank into a larger spatial context, a 60-km wide swath adjacent to the coast, extending

from 40 - 48°N was extracted from the monthly chlorophyll time series. Chlorophyll concentrations were averaged in the cross-shelf direction and then smoothed using a 4 x 4 median filter in the along-shelf direction as well as in time to fill in missing data.

Chapter 3

RESULTS

3.1 Seasonal Chlorophyll Variability

The climatological seasonal variability of chlorophyll concentrations on Heceta Bank is shown in Figure 3.1 and compared to that north and south of the bank on the shelf (90-100 meters). A seasonal cycle, with lowest concentrations in the fall, winter and spring (1.0-2.5 mg m^{-3}) and maximum in the summer (5-6.5 mg m^{-3}) is evident at all three locations. The seasonal increase in chlorophyll concentration occurs in June, peaks in July on Heceta Bank (6.5 mg m^{-3}) and the southern site (5.5 mg m^{-3}) and in August at the northern site (5.3 mg m^{-3}). Relatively low fall-winter concentrations are re-established by October for all three locations.

To quantitatively describe the predominant time and space patterns of chlorophyll on Heceta Bank in context of the whole Oregon upwelling region, an empirical orthogonal function decomposition (EOF) of the 4-year time series of monthly composite chlorophyll images was calculated using a covariance matrix. The dominant mode of the EOF (Figure 3.2) represents 41.7% of the total variance and reveals a relatively simple spatial pattern spanning the entire study area of elevated values nearshore and lower values offshore. This pattern is enhanced in strength and cross-shelf extent over Heceta Bank and is very similar to the pattern of shelf bathymetry. The amplitude time series associated with this pattern (Figure 3.2) captures the overall seasonality with peaks in the summer months and minima through the other seasons. The time series provides evidence of a weak spring increase in most years that was not evident in Figure 3.1 due to

interannual variability in its exact timing. Other weaker modes produced by this EOF contained additional seasonality but were also influenced by clouds (missing data) and are not discussed here.

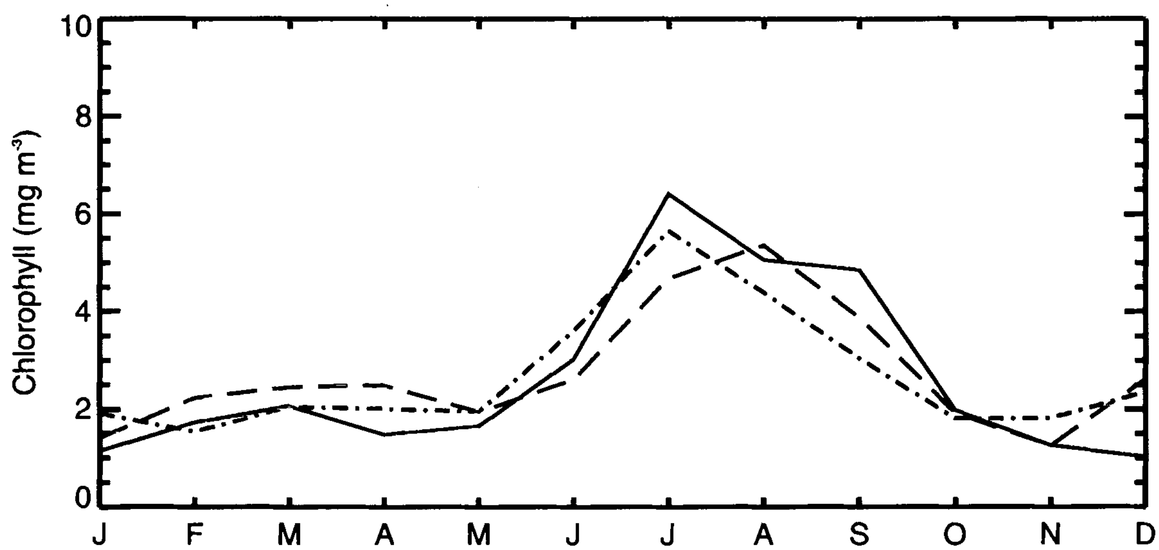

Figure 3.1 - *4-Year Monthly Chlorophyll Climatology on the Shelf at 3 Study Locations*
The monthly seasonal cycle of shelf chlorophyll concentrations (similar depth) is shown over Heceta Bank (blue solid line), south of the bank (red dashed-dotted line) and north of the bank (green dashed line).

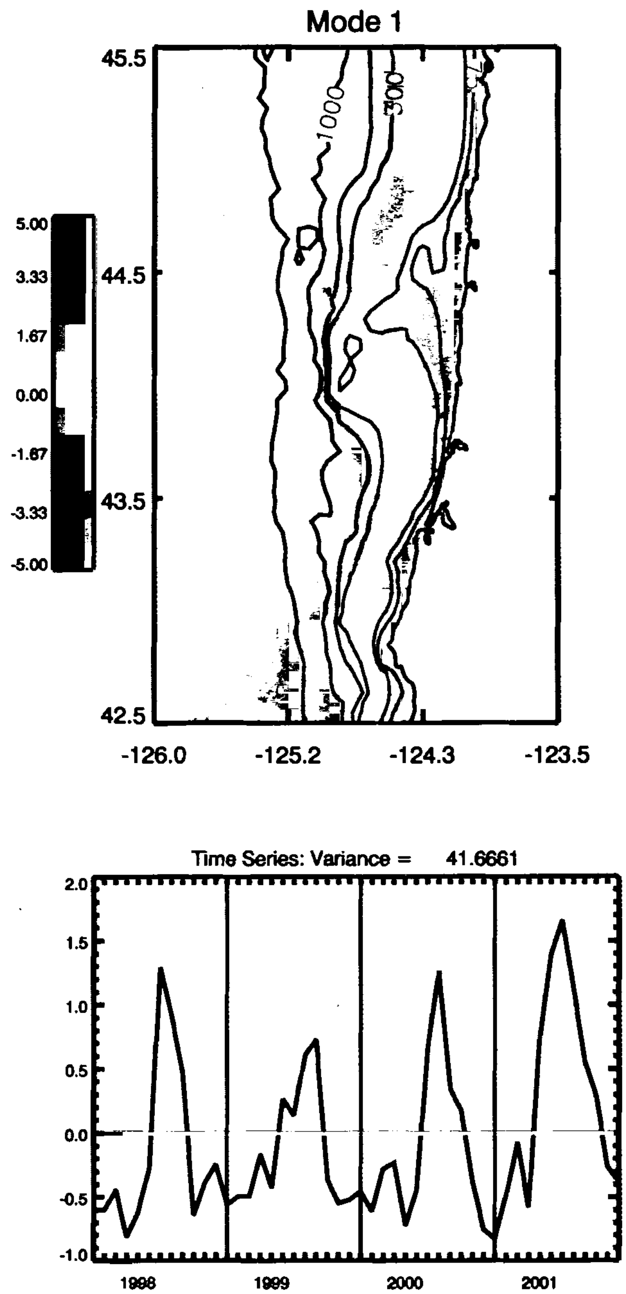

Figure 3.2 - *Dominant Mode of 4-Year Climatological EOF Decomposition*
Mode 1 of the EOF decomposition of the 4-year climatology shows the spatial pattern of elevated chlorophyll concentrations on the shelf and the amplitude time series of this spatial pattern. Bathymetric contours have been overlayed to show location of Heceta Bank.

3.2 Latitudinal and Interannual Chlorophyll Variability

Chlorophyll concentrations, contoured as a function of time and distance from shore at the three study latitudes show the cross-shelf extent and temporal duration of chlorophyll on the shelf throughout the study period (Figure 3.3a,b, c). At all three locations a clear general seasonal cycle of summer maxima and winter minima is superimposed on considerable interannual variability. Figure 3.2 shows the strongest year to be 2001 and the weakest year to be 1999. Over Heceta Bank (44.0 - 44.25°N, Figure 3.3b) higher concentrations (> 4 mg m^{-3}) are confined to the shelf (within 55 km of the coast) in all four years, extending farthest offshore in 2000 and 2001 (50 km) and confined most closely to the coast in 1999 (15 km). Over the relatively narrow shelf south of Heceta Bank (43.0 – 43.25°N, Figure 3.3b), chlorophyll concentrations > 4 mg m^{-3} are still confined to within 35 km of the coast but extend up to 20 km beyond the shelf break during the summer in three of the four study years (1998, 2000, and 2001). The interannual maximum (2001, 25.5 km) and minimum (1999, 5 km) in the offshore extent of high chlorophyll concentrations is the same as those observed over the bank. North of Heceta Bank (45.0 – 45.35°N, Figure 3.3c) the shelf is wider than the southern site but slopes more steeply than that over the bank. Chlorophyll concentrations > 4 mg m^{-3} extend to and in some cases beyond the 100 m contour isobath in all years, but this is within 20 km of the coast. Maximum offshore extension of high chlorophyll concentrations in this extension area occurred in 1999 and 2000 (15 km). The weakest year was 1998 (10 km).

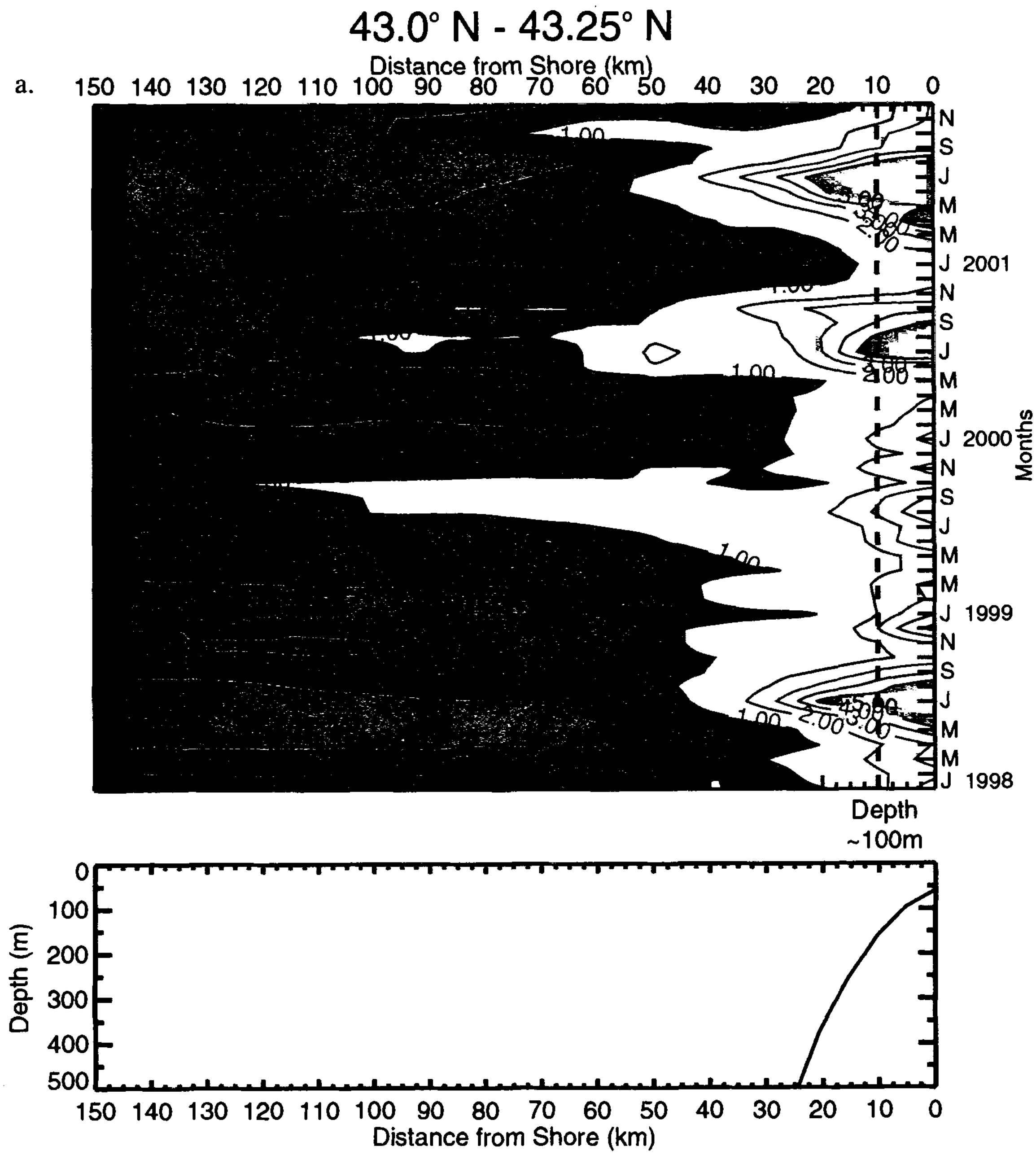

Figure 3.3 - *Cross-shelf Monthly Chlorophyll Contours and Bathymetry*
a. Cross-shelf profile of monthly chlorophyll concentration(mg m^{-3}) contoured as a function of cross-shelf distance and time for the three study locations. The bottom shows the cross-shelf bathymetric profile. The dashed line marks the location of the 100m isobath.
a) South of the bank , b) Heceta Bank, c) North of the bank.

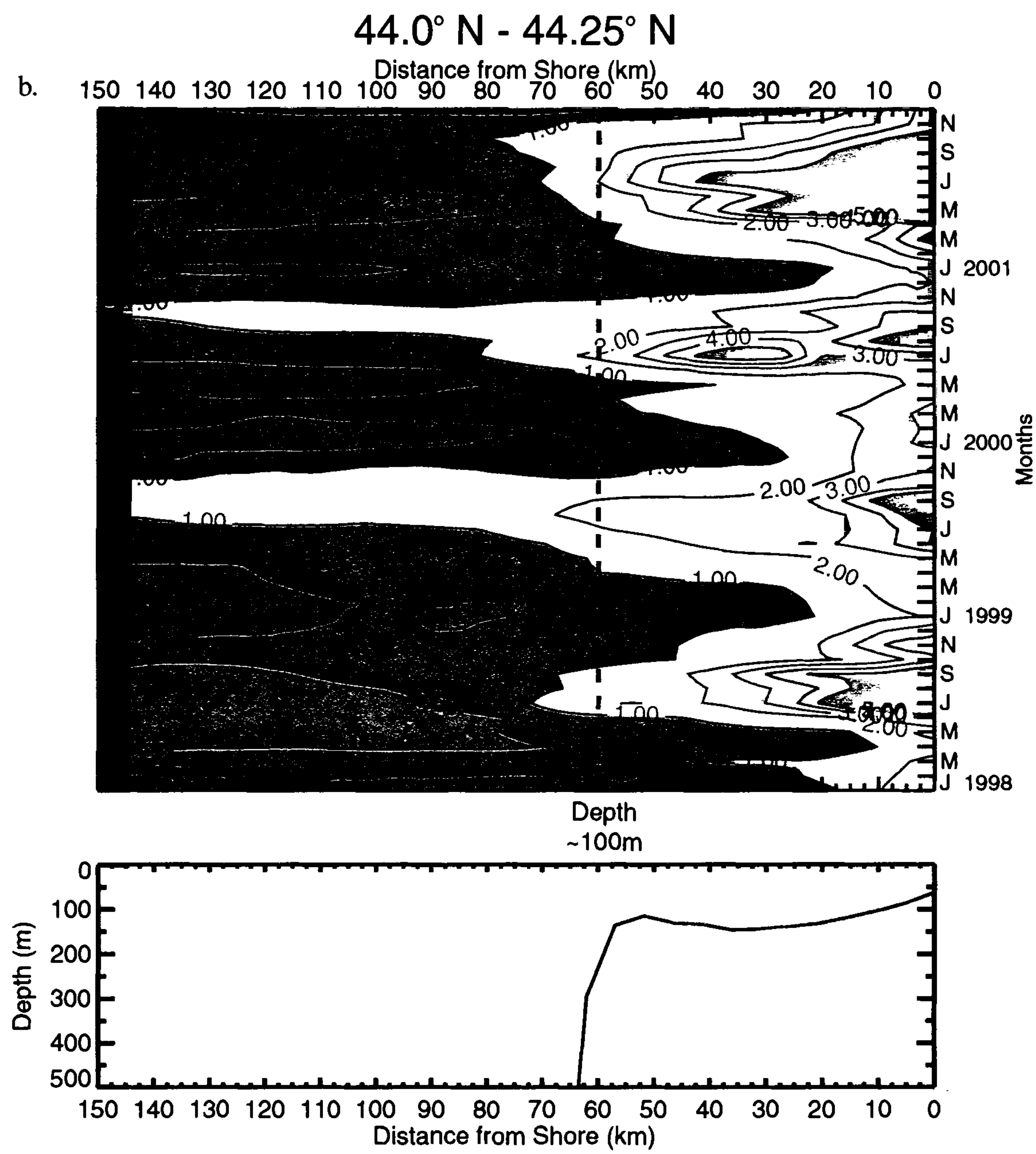

Figure 3.3 continued.
b. For figure caption see Figure 3.3a

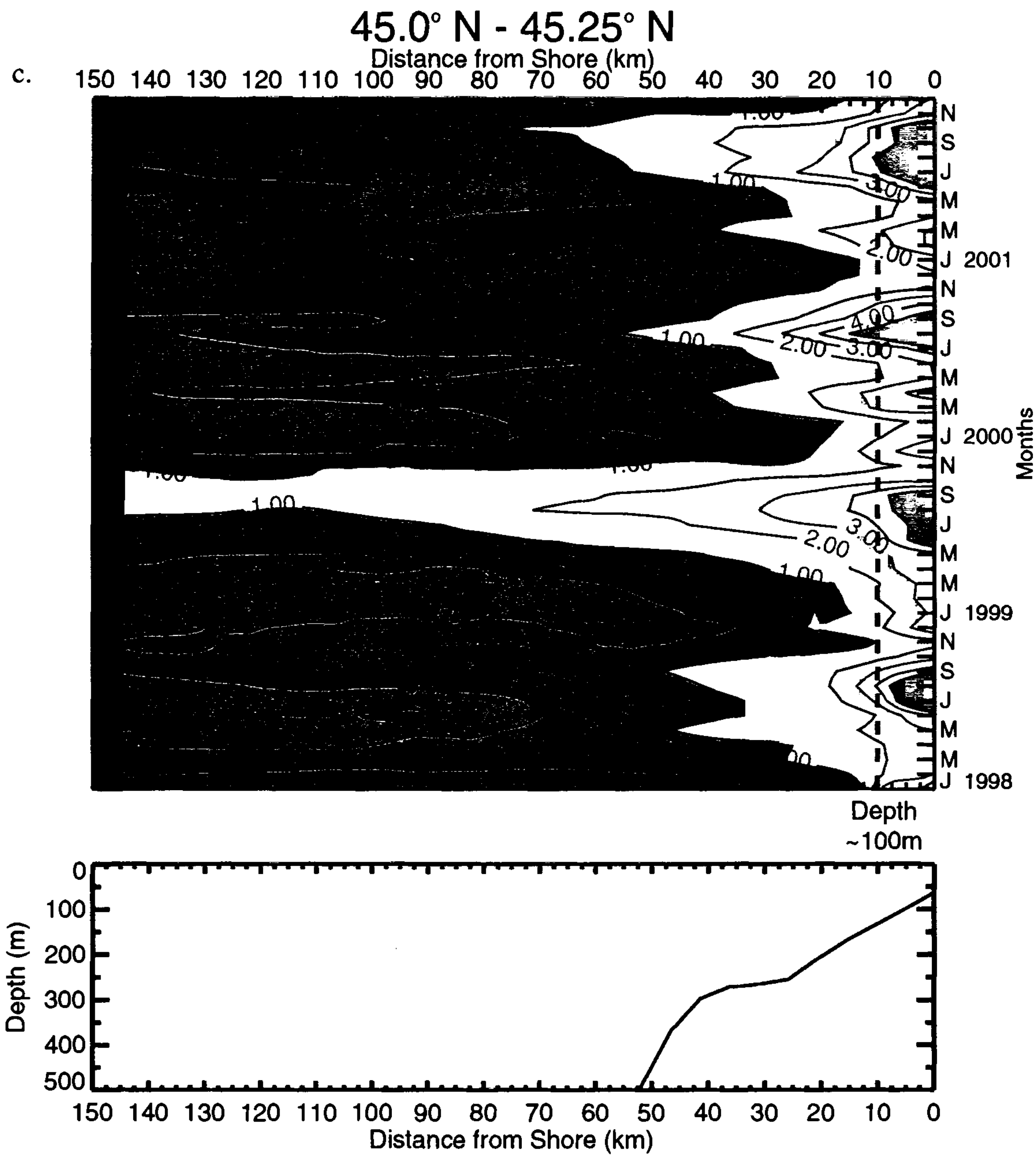

Figure 3.3 continued.
c. For figure caption see Figure 3.3a

Figures 3.2 and 3.4 show that the shelf width affects the cross-shelf extent of chlorophyll off the Oregon coast. The dominant mode of the EOF (Figure 3.2) also shows that concentrations are maximum in coastal regions, particularly on the bank. Thus, shelf width may also play an important role in the actual chlorophyll concentrations found in the coastal ocean. A greater shelf width may increase the availability of nutrients, such as iron, whose sources to ocean water include bottom sediments and land runoff. Increased mixing on wider shelves may also keep nutrient levels higher. The shelf extends further offshore over Heceta Bank than the adjacent shelf regions. A change in physical forcing around such a feature may impact the transport and/or retention of phytoplankton impacting chlorophyll concentrations. Wind forcing along a straight coastline, like Oregon, results in a relatively straight upwelling front. Changes in shelf width may also alter the cross-shelf distribution of chlorophyll by extending the upwelling front further offshore. Comparing the variability of chlorophyll at locations of equal distance from shore and contrasting these with variability at similar bathymetric cross-shelf locations allows us to examine the effect of a wider shelf on chlorophyll concentrations (Figure 3.5b). Means were extracted from 25 x 25 km boxes north and south of the bank at locations equal distances from the coast as the center of Heceta Bank (45.17°N, 124.27°W and 43.17°N, 124.68°W). Depths at these locations are > 100 m and < 200 m. Although specific differences between sites are evident on the shelf (depths < 100 m), these are not consistent from year to year and chlorophyll variability at the northern and southern sites is similar to that on Heceta Bank (Figure 3.5a). At an equal distance from shore (20 km) (Figure 3.5b) however, the northern and southern sites have

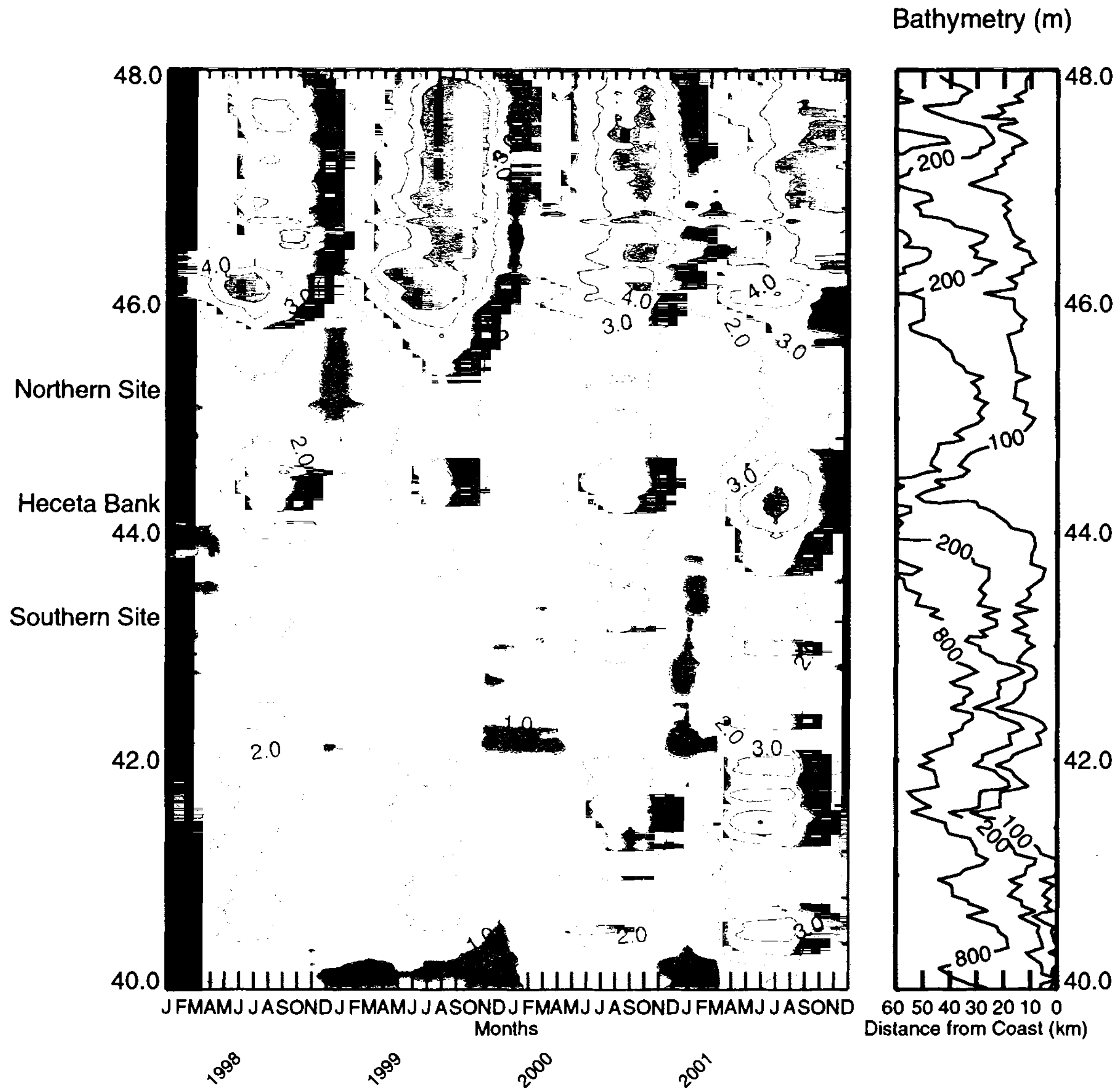

Figure 3.4 - *Along-shelf Monthly Chlorophyll Contours of the Oregon/Wasington Coast* Monthly chlorophyll concentrations (mg m^{-3}) over the 60km closest to the coast contoured as a function of latitude and time over the Washington, Oregon, and northern California (Cape Mendocino). For comparison the right panel shows along-shore bathymetry (meters).

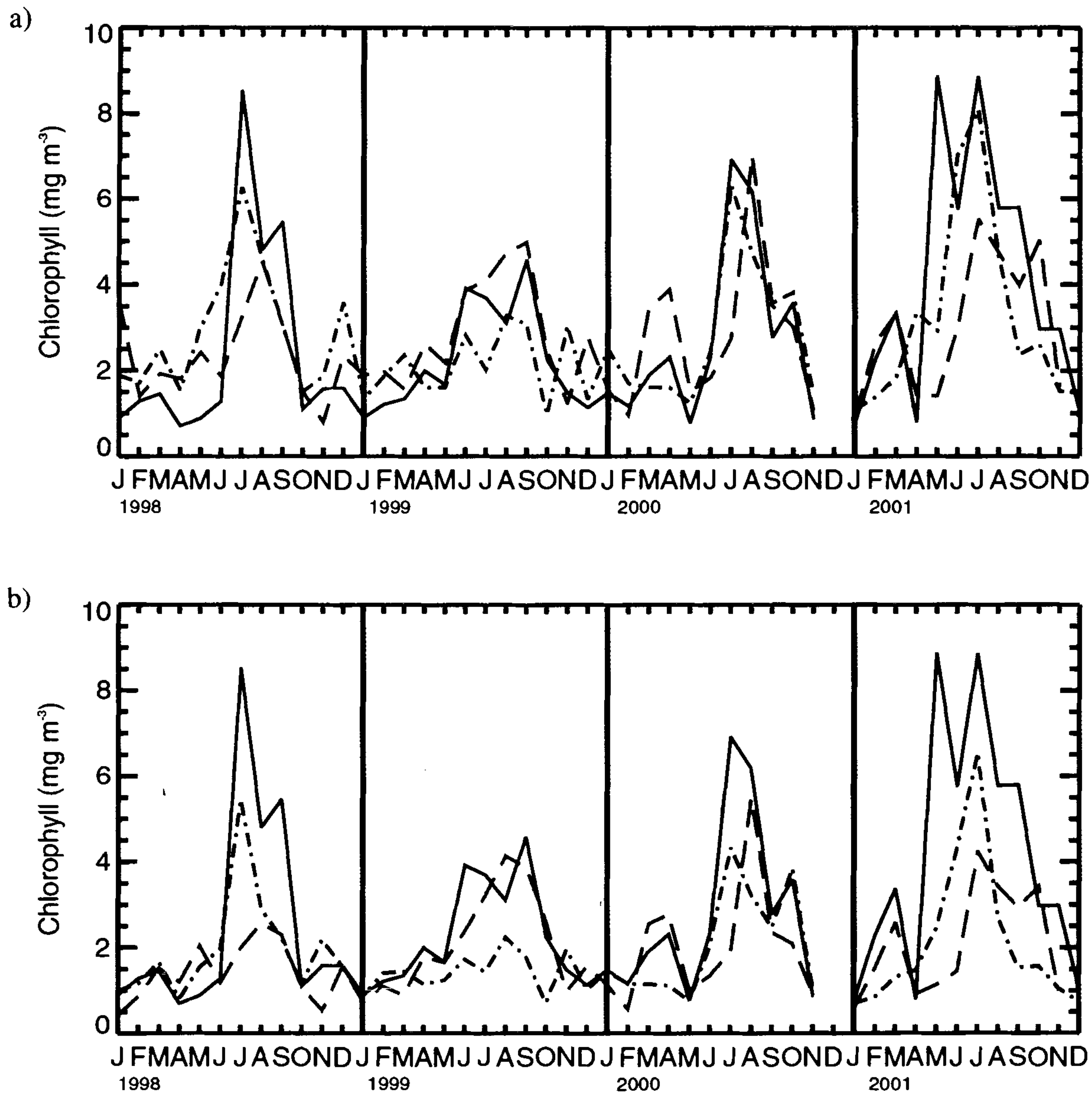

Figure 3.5 - *4-Year Time Series of Monthly Chlorophyll at 3 Study Locations*
Monthly interannual chlorophyll concentrations a) on the shelf (similar depth) and b) equidistant from the coast (20 km) from the 4-year monthly time series is shown for Heceta Bank (blue solid line), south of the bank (red dashed-dotted line), and north of the bank (green dashed line).

consistently weaker chlorophyll concentrations than those over Heceta Bank, primarily due to reduced summer maxima. The position of the upwelling front at the northern and southern locations may play a role in the weaker chlorophyll concentrations observed. The shelf width at these two locations is narrower than over Heceta Bank possibly causing the upwelling front to be closer to shore. Qualitative observations of chlorophyll and SST images suggest that 20 km from the coast north and south of the bank sometimes is the edge of the upwelling front. The wider shelf over Heceta Bank may keep the upwelling front further offshore. Low salinity Columbia River water offshore may also play a role in the position of the upwelling front.

Interannual variability in maximal summer chlorophyll concentrations shows Heceta Bank and the southern site behave similarly. Both Heceta Bank and the southern site develop highest chlorophyll concentrations in the summers of 1998 (8.5, 5.4 mg m^{-3}) and 2001 (9.0, 6.5 mg m^{-3}) and minimal summer concentrations in 1999 (2.3, 4.5 mg m^{-3}) (Figure 3.5b). North of the bank, however, maximal concentrations occur in 2000 (5.5 mg m^{-3}) and minimal concentrations occur in 1998 (2.5 mg m^{-3}).

Variability of chlorophyll concentrations within ocean color data in both space and time can be used as an indicator of data consistency, accuracy and overall quality. Standard error was calculated for the monthly chlorophyll data sampled from the 25 x 25 km boxes at each study location in both space and time. Variability in chlorophyll values over the 25 x 25 km area was calculated over each box in each monthly composite in the time series to estimate the. These values of spatial standard error ranged from 0.0045 - 0.7674 mg m^{-3} over the study period at the three locations with 88% of the values less than 0.1 mg m^{-3}. Over the time series, spatial standard error was highly variable. In most

months, however, all three study locations had similar error values, with no apparent consistent relationship between chlorophyll values and spatial standard error values. These results indicate that variability over each sample box is controlled at all three locations by similar forcing or instrument noise. Low error values also suggest event scale pulses in chlorophyll concentrations are smoothed out over the monthly average and a 25 x 25 box average of these values is an accurate representation of the data over that area. Temporal standard error was calculated for a time series of daily 25 x 25 km box averages at each location for each month to estimate how variable average chlorophyll values are within each month. The temporal standard error ranges from 0.0176 - 4.0782 mg m^{-3} with 88% of the calculated values less than 1.0 mg m^{-3}. The low value of errors over the time series suggests that a monthly average of these values is a good estimation of chlorophyll concentrations over the entire month. These temporal errors also behave similarly at all three locations. Although higher errors are often associated with higher chlorophyll concentrations, e.g. temporal standard error is highest in the summers of 1998 and 2001, a clear seasonal cycle in error values, is not evident over the whole time series suggesting that variability of chlorophyll concentrations on daily scales within each month is independent of seasonal forcing. The low spatial and temporal standard error values suggest seasonal differences (Figure 3.1) as well as interannual differences in chlorophyll concentrations between locations (Figure 3.5) can be interpreted as actual differences and not artificial differences due to error within each chlorophyll average.

The timing of the seasonal increase in chlorophyll concentrations varies interannually and also with latitude. Using the zero crossing of the EOF (Figure 3.2) as a metric, the regional spatial pattern becomes positive in each year between June and July except in

2001 where positive values begin in May. Figure 3.3a,b and c provide a clear picture of latitudinal variability in seasonal development. South of the bank, with the exception of 2001, the onset of summer high chlorophyll concentrations (> 4 mg m^{-3}) is usually in May-June. On Heceta Bank and north of the bank this onset occurs in June-July (except May in 2001).

The summer of 2001 had the longest sustained period of elevated chlorophyll on the inner shelf at all three locations (Figure 3.3). Elevated chlorophyll lasted seven months (May – November) over Heceta Bank, four months north of the bank (July-October) and five months south of the bank (April – August). In contrast, concentrations > 4 mg m^{-3} lasted for only one month on the bank in 2000 (August) and south of the bank in 1999 (August). The shortest sustained summer high chlorophyll concentrations north of the bank is 2 months in 2000 (August – September). Duration of elevated chlorophyll as seen in Figure 3.3 may be blurred due to smoothing of the data in time prior to contouring. Similar interannual patterns of sustained elevated chlorophyll however, are also observed in Figure 3.5a where the data was not smoothed in time.

Chapter 4

DISCUSSION

4.1 Seasonal Variability

The seasonal pattern of chlorophyll observed in the EOF (Figure 3.2) and the 4-year climatology (Figure 3.1) agrees with the general seasonal cycle previously observed by other researchers [*Thomas and Strub,* 2001; *Strub et al.,* 1990; *Landry et al.,* 1989]. *Thomas and Strub* [2001] examined the cross-shelf pigment variability averaged over the entire Oregon/Washington coast. They describe a spring maximum, summer relaxation, fall maximum and winter minimum in cross-shelf phytoplankton distribution. The summer relaxation in cross-shelf distributions is attributed to a reduction in mixing and nutrient availability offshore. The seasonal pattern of chlorophyll described by *Thomas and Strub* [2001] however, exists further offshore than the shelf and shelf break region examined in this study and the results presented here offer a more detailed look at shelf patterns not resolved by *Thomas and Strub* [2001]. Although in most years (1998, 2000, 2001), the data presented here indicates a summer relaxation of cross-shelf chlorophyll distributions (Figure 3.3) similar to the offshore pattern described by *Thomas and Strub* [2001], the 4-year climatology of coastal chlorophyll concentrations (Figure 3.1) over the Oregon shelf region does not indicate a summer relaxation. Persistent upwelling, recirculation and perhaps coastal shelf tidal mixing may keep chlorophyll concentrations consistently elevated throughout the summer season over Heceta Bank and the shelf regions north and south.

The seasonal increase in chlorophyll begins in May, after the spring transition to upwelling favorable winds [*Strub et al.*, 1990]. Figure 3.1 shows that peaks in summer chlorophyll occur first at 43°N and Heceta Bank (July) and then later at 45°N (August). This delayed seasonal chlorophyll maximum at the northern site is consistent with the seasonal progression of local wind forcing. During the summer upwelling season maximum wind stress occurs off northern California [*Strub et al.*, 1987]. Summer wind stress decreases with increasing latitude. Previous research has shown that the offshore Ekman transport is 3-4 times larger near Cape Blanco than off the coast of northern Oregon [*Samelson et al.*, 2002]. Figure 4.1 shows the PFEL wind-derived upwelling index at 42°N and 45°N for 1998-2001. Upwelling is stronger at 42°N than at 45°N, consistent with the findings of a decrease in alongshore wind stress with increasing latitude by *Samelson et al.* [2002]. A return to wintertime levels of chlorophyll occurs at all three locations by October (Figure 3.1). The timing and duration of the seasonal pattern of chlorophyll on Heceta Bank agrees with the regional trends in local wind forcing evident along the entire Oregon coast.

An examination of the mean SST seasonal cycle at the three study locations also indicates that Heceta Bank's seasonality behaves similarly to the rest of the Oregon shelf (Figure 4.2). Warming begins in May, maximum SST occurs in August and by November SSTs approach winter values. In the summer months, the northern site is the warmest (15.0°C) and the southern site is the coldest (13.1°C) with Heceta Bank intermediate between the two (14.5°C). During winter, Heceta Bank and the southern site have similar temperatures (11.0-11.5°C) and the northern site is cooler (10.5-11.0°C). The gradation of summer SST seen in Figure 4.2 agrees with the gradation of decreasing

upwelling wind stress observed by *Samuelson et al.* [2002]. Stronger and/or more consistent upwelling would result in the cooler summertime temperatures observed at 43°N. Weaker and/or more intermittent upwelling would result in the warmer temperatures at 45°N.

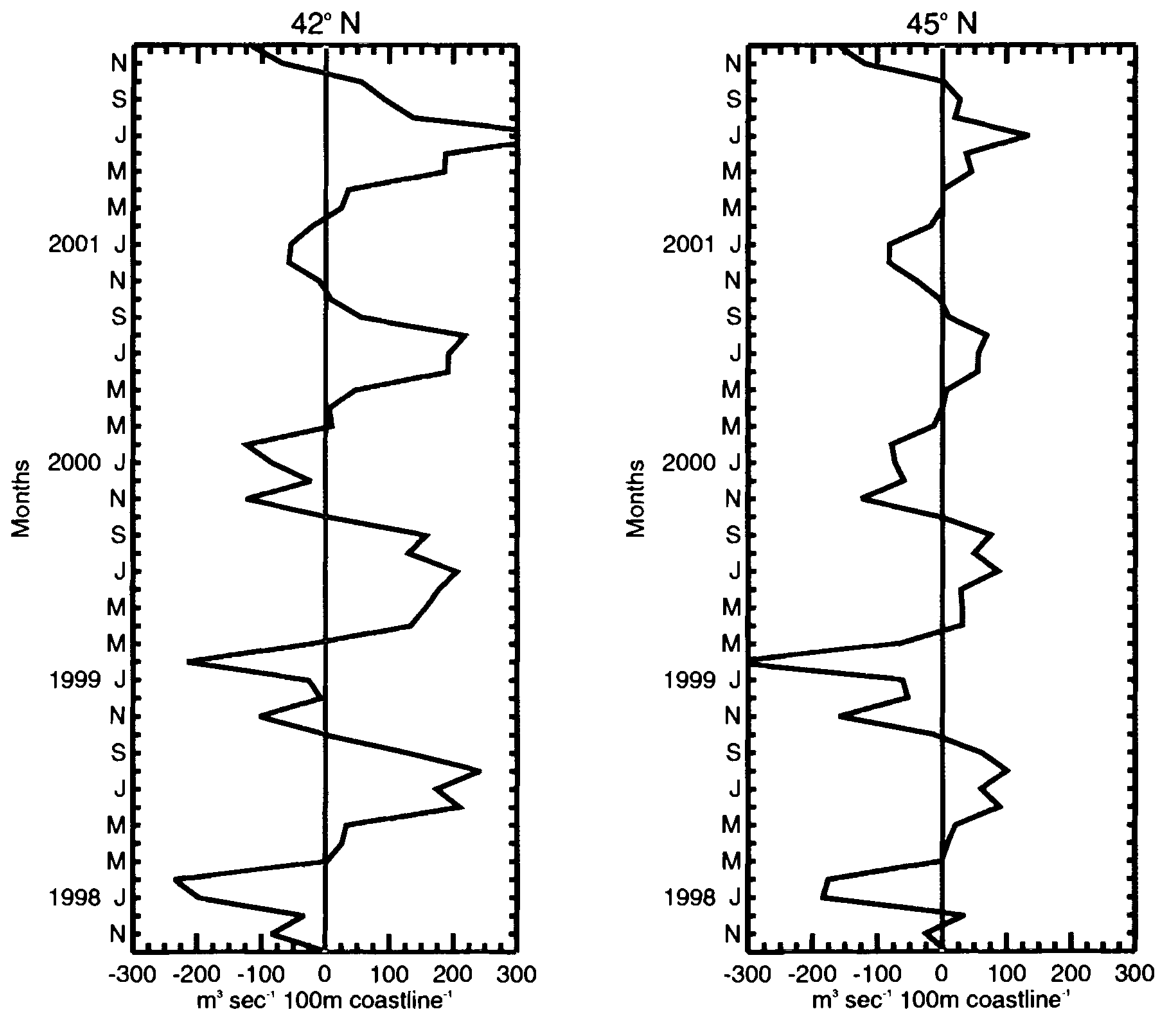

Figure 4.1 - *PFEL Upwelling Index at 42ºN and 45ºN*
PFEL upwelling index for 1998-2001 calculated as offshore Ekman transport due to wind stress. Positive values mean upwelling conditions. Negative values mean downwelling conditions.

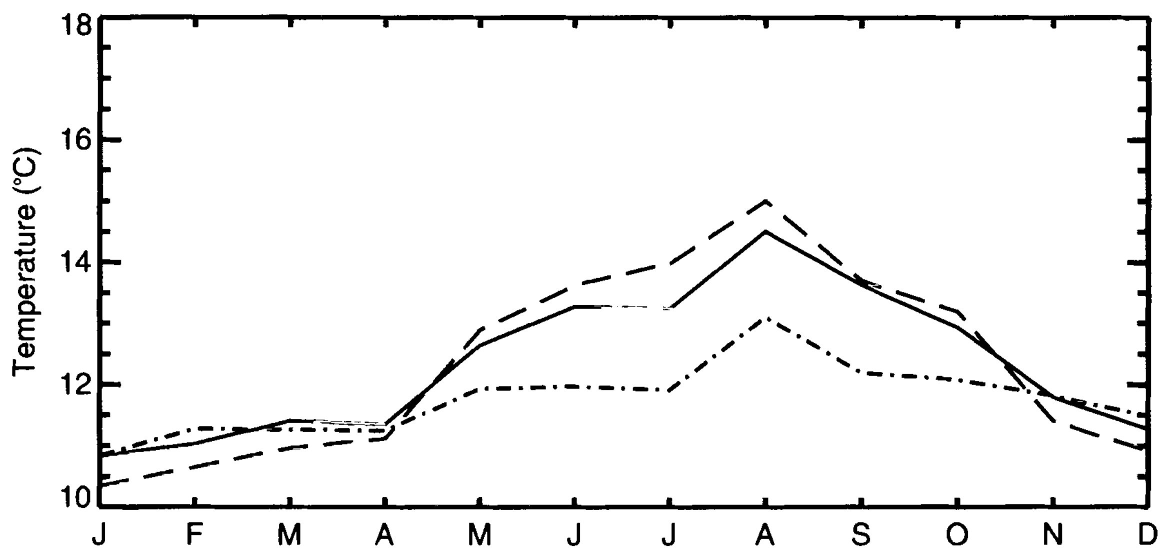

Figure 4.2 - *4-Year Monthly SST Climatology on the Shelf at 3 Study Locations*
The monthly seasonal cycle of shelf sea surface temperature (similar depth) is shown over Heceta Bank (blue solid line), south of the bank (red dashed-dotted line), and north of the bank (green dashed line).

4.2 Interannual Variability

Over the period 1998-2001, the strongest monthly summer chlorophyll concentrations on the shelf were present in 2001 (Figure 3.2). Figure 3.5a shows that during this year, maximum chlorophyll concentrations were observed at both 43°N and Heceta Bank (8.0 and 9.0 mg m^{-3}) and the duration of summer shelf-intensified chlorophyll was the longest at all three locations (5 months on Heceta Bank and 3 months at 43°N and 45°N). Figure 3.3 shows that these concentrations are associated with a maximum in cross-shelf extension of elevated chlorophyll concentrations over both Heceta Bank and at 43°N. The 4-year time series of shelf SST at the three study locations shows a trend of increasingly colder summers over the study period (Figure 4.3). Minimum SSTs in 2001 are at least partially consistent with interannual wind forcing. The PFEL upwelling index is strongest in the summer of 2001 at 42°N. The relationship is less clear at 45°N, but July 2001 is the strongest offshore transport in the time series (Figure 4.1). At 42°N the duration of summer upwelling in 2001 is larger than previous years, beginning in March and transitioning back to downwelling winds in October. Increased wind-driven upwelling and colder summer SSTs are a consistent explanation for the higher and more sustained summer chlorophyll concentrations over the shelf in 2001. At 45°N, it is less clear that wind forcing is stronger in 2001 than earlier years. The clear negative trend in summer SSTs, however suggests that forcing other than what is measured here, such as subsurface hydrographic changes in temperature and nutrient concentrations, are likely involved in determining the surface signatures seen in satellite imagery.

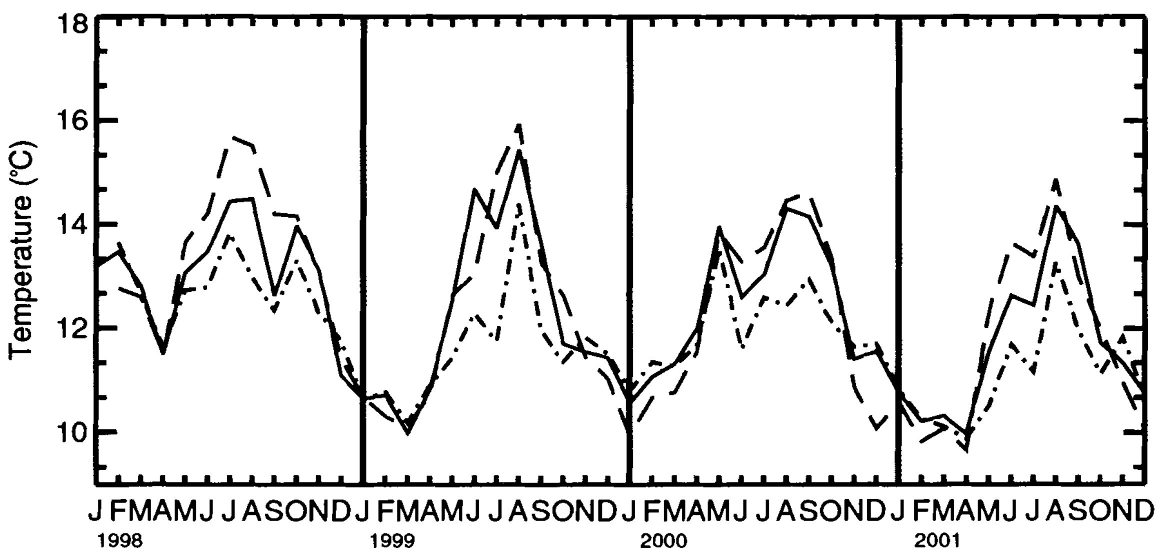

Figure 4.3 - *4-Year Time Series of Monthly Shelf SST at 3 Study Locations*
Monthly interannual sea surface temperature (similar depth) is shown over Heceta Bank (blue solid line), south of the bank (red dashed-dotted line), and north of the bank (green dashed line).

The weakest summer chlorophyll concentrations on the shelf were evident in 1999 (Figure 3.2) with maxima of 3.0-5.0 mg m^{-3} at the three study sites (Figure 3.5a). Cross-shelf extension (Figures 4a, b, c) of the highest coastal chlorophyll concentrations (> 4.0 mg m^{-3}) was also least during this year at two of the study sites (43 and 44°N), although total extension of weaker chlorophyll concentrations (1.0-2.0 mg m^{-3}) was maximum in this year. The reduced chlorophyll concentrations nearshore are consistent with the warmest summer shelf temperatures (15-16°C) at all three locations in 1999 (Figure 4.3). La Nina conditions were present over the Pacific basin, including the Oregon coast, in July/August 1998-1999 [*Huyer, et al.*, 2002; *McPhadden*, 1999]. Although the transition from the El Nino conditions to La Nina conditions was very rapid [*McPhadden*, 1999], anomalies of steric height, temperature, salinity and the PFEL upwelling index were all weaker than during previously observed La Nina events off the Oregon coast [*Smith et al.*, 2001]. Figure 4.1 shows that local wind forcing was average during the summer of 1999 with respect to the other three study years. Although La Nina conditions of 1999 do not appear to influence chlorophyll concentrations or strength of upwelling in the shelf region of the Oregon coast, maximum cross-shelf extension of weaker chlorophyll values do suggest a positive influence of La Nina on chlorophyll concentrations offshore.

Evidence of the 1997-98 El Nino event has been found along the Oregon coastline by other researchers [*Huyer et al.*, 2002; *Smith et al.*, 2001; *Thomas and Strub*, 2001]. By September 1997, *Huyer et al.* [2002] observed a rise in sea level near the coast, a deepening of the thermocline, and enhanced poleward advection of water along the continental slope of the Oregon coast. *Smith et al.* [2001] also observed anomalously high steric heights near shore and positive surface and subsurface temperature anomalies

between July 1997 and September 1998. At a regional scale, *Thomas and Strub* [2001] found that the maximum cross-shelf distribution of chlorophyll > 1-2 mg m^{-3} occurred later in the summer season (September) during the 1997-98 El Nino year than previous years available in the CZCS dataset. Figure 3.3 shows a peak in the cross-shelf extension of chlorophyll concentrations 1-2 mg m^{-3} in August and September. The onset of chlorophyll concentrations > 2 mg m^{-3} are delayed until July on both Heceta Bank and 45°N, however the cross-shelf extension of those concentrations was not delayed suggesting local forcing may overcome the effects of El Nino closer to shore. Inshore, elevated summer chlorophyll concentrations on Heceta Bank were present for a relatively short period (July, August, September) in 1998 (Figure 3.5a) and surface temperatures in the winter and early spring (January-May) of 1998 were warmer than those of the other three years in this study (Figure 4.3) consistent with the observations made by *Huyer et al.* [2002] and *Smith et al.* [2001]. El Nino may delay the onset of the summer elevated chlorophyll with warmer spring temperatures, inshore however, local forcing may overcome the delay.

The El Nino signal (delayed summer chlorophyll increase) in early 1998 evident at the 2 northern sites was not present at the southern site (43°N) (Figure 3.5a). Wind forcing at 42°N is stronger than over Heceta Bank and 45°N (Figure 4.1). Previous work [*Huyer et al.*, 2002; *Smith et al.*, 2001; *Chavez*, 1996] has shown that local wind forcing during El Nino in the CCS is often not reduced and in some cases is actually stronger than normal. Close to shore, upwelling at 43°N may have been strong enough to overcome the warmer spring temperatures and initiate the spring increase in chlorophyll concentrations in April. On Heceta Bank and farther north, reduced wind forcing in conjunction with

warmer spring SSTs appear to delay the onset of the seasonal increase in chlorophyll concentrations.

When quantifying seasonal and interannual variability of satellite-measured chlorophyll, variability associated with averaging over both time and space must not be neglected. Visual inspection of a time series of daily chlorophyll scenes, particularly in coastal regimes, reveals high variability in both these dimensions. An examination of both temporal and spatial standard error indicates seasonal values are statistically different, differences between study locations for each month however, are typically within similar margins of error. An additional source of variability is the number of valid returns at each location over a month. In areas or seasons where cloud cover is high, the number of valid returns from the satellite will be low. Along the Oregon coast, persistent cloud cover is a common problem, particularly in winter. The average number of valid daily returns over a 25 x 25 km box area at any one of the study locations sampled from a monthly composite is usually below 5 during the winter months. Highest average returns of 10-15 occur in the late summer and early fall. These values suggest winter monthly composites may provide a bias picture of spatial patterns over the month. Summer monthly composites provide a better estimate of the true mean monthly chlorophyll patterns. Although potentially bias, these scenes still provide our best available quantification of seasonal and temporal spatial patterns in this region.

Another possible bias in satellite-measured chlorophyll estimates of the Oregon coast could result from suspended sediment and/or color dissolved organic matter (CDOM) from river discharge, especially the Columbia River. CDOM biases chlorophyll estimates in coastal waters [*Arnone and Gould,* 1998; *Morel and Prieur*, 1977]. Low salinity

waters containing suspended sediments (and color dissolved organic matter or CDOM) from the Columbia River have been found in coastal waters off Oregon during the summer months [*Landry et al.*, 1989; *Hickey*, 1989]. An estimate of the relative influence of the Columbia River plume on the spectral irradiance values recorded by SeaWiFS was made through a preliminary examination of the spectral signatures at five different points along the Oregon coast during the four seasons. The results showed the spectral signature of the Columbia River plume to be variable throughout the year. The plume was spectrally different from the other 4 locations in the winter and spring. During the fall, when the flow velocity out of the river is at a seasonal minimum, the spectral signature of the plume was similar to the other points along the Oregon coast. In the summer, the radiance spectrum at the mouth of the Columbia River was highly variable, at some times appearing distinctly different from the other locations and at other times appearing very similar. It was concluded that CDOM from the Columbia River present in the coastal shelf waters along the Oregon coast periodically bias the satellite chlorophyll estimates of this region (by artificially enhancing the estimates). Patterns of chlorophyll concentrations may also be biased. The plume may meet the upwelling front offshore making it appear the chlorophyll concentrations reach farther offshore than they actually are at the surface. The cold, saline upwelled water being transported offshore might subduct underneath the less saline river water bringing high chlorophyll concentrations with it. A more comprehensive study is required to quantify the degree of influence the Columbia River has on satellite chlorophyll measurements of this area.

4.3 Correlations between Chlorophyll, Temperature and Wind Forcing

Linkages between hydrographic conditions and biological response in the study area were explored by correlating shelf chlorophyll and temperature over the 4-year time series. The temporal decorrelation time scale of phytoplankton pigment patterns is on the order of 2-5 days for spatial scales of 25-50 km [*Denman and Abbott*, 1988]. Surface SST and chlorophyll spatial patterns evolve simultaneously in coastal upwelling regimes [*Denman and Abbott*, 1994]. To obtain samples of chlorophyll concentrations and SSTs statistically independent in both time and space, boxes (25x25 km) on the shelf were extracted from the time series of 8-day SeaWiFS and AVHRR composites. The climatological seasonal cycle was removed from each time series and then each resulting anomaly series was detrended. Correlations were calculated between the resulting anomaly time series of chlorophyll, temperature and chlorophyll vs. temperature. Autocorrelations of 25x25 km average daily anomaly time series for chlorophyll and SST data at each study site indicated a decorrelation time scale of 1-4 days, suggesting that each 8-day composite could be treated as statistically independent. Table 4.1 shows that temporal variability of Heceta Bank chlorophyll anomalies are significantly correlated (98%) to that at both the northern and southern sites. These spatially separated sites, however, are not significantly correlated to each other. Local bathymetry and wind may control the timing of chlorophyll concentrations resulting in a spatial decorrelation scale of 120 km over an 8-day period. At a 240 km distance the correlation of shelf chlorophyll is insignificant.

Unlike chlorophyll, non-seasonal SST variability is strongly correlated between all three study locations (Table 4.1). This correlation implies that forcing on spatial scales > ~100 km controls shelf SST variability, along the Oregon coast north of Cape Blanco, at least over the 8-day periods examined here. A comparison of Figures 4 and 7 suggest that latitudinal differences in wind forcing dominate alongshore SST variability. The southern site has strongest wind forcing and the coldest temperatures. The northern site has the weakest wind forcing and the warmest temperatures. One may hypothesize that increased mixing on the bank may cause water to be colder than other areas along the shelf of similar depth. Heceta Bank however, has moderate upwelling and temperatures compared to the other two locations.

	SST44	SST43	SST45	CHL44	CHL43	CHL45
SST44	1					
SST43	***0.767***	1				
SST45	***0.714***	***0.646***	1			
CHL44	***-0.331***	-0.262	-0.248	1		
CHL43	-0.102	***-0.329***	-0.008	***0.370***	1	
CHL45	-0.113	-0.204	***-0.28***	***0.243***	*0.126*	1

Table 4.1 – *Pearson Correlation Coefficients for Chlorophyll and SST*
Pearson correlation coefficients of 8-day chlorophyll concentrations and 8-day temperature at each of the three study locations for 1998-2001. Bolded values are significant at 98%. Italicized values are discussed in the text. The 98% significance value with 111 degrees of freedom is 0.219.

The non-seasonal temporal variability of chlorophyll and SST is significantly negatively correlated at zero lag at all three locations (Table 4.1). Negative correlations imply colder temperatures are associated with higher chlorophyll concentrations, consistent with canonical upwelling theory. Although upwelling events often last only 3-10 days [*Hill et al.*, 1998], chlorophyll and temperature can remain correlated over larger periods. Phytoplankton cells behave as passive particles at mesoscales and *Denman and Abbott* [1994] concluded that the growth, death and sinking of phytoplankton together play a marginal role in determining chlorophyll spatial patterns in active upwelling regions. The temporal response of chlorophyll spatial patterns to an upwelling event can be delayed by 1-2 days [*Denman and Abbott*, 1994] thus the 8-day mean of chlorophyll and temperature examined here likely smoothes over this time lag allowing the correlation to remain high.

The daily PFEL upwelling indices were binned to 8-day averages for comparison to the chlorophyll and SST data sets. Significant correlations between either chlorophyll or SST and wind forcing within our 8-day time series were not present. These results are consistent with poor correlations found by *Strub et al.* [1990] between wind forcing and chlorophyll in monthly averages. While chlorophyll concentrations within an upwelling zone are related to changes in the wind field over 10-20 day time scales, it is possible that local alongshore wind is too variable to correlate well with changes in chlorophyll concentrations over shorter time scales [*Thomas and Strub*, 2001]. *Kelly* [1985] found SST and wind stress to be related off the northern California coast. Winds off northern California, however, are stronger than off Oregon possibly improving the relationship between wind and SST.

4.4 Bathymetric Effects on Variability

Temporal variability in the Heceta Bank region is put into a larger-scale context by comparing mean chlorophyll concentrations within 60 km of the coast over the entire Washington/Oregon/Northern California coastal region (Figure 3.4). Our data show that north of 46°N, persistent summer chlorophyll concentrations > 3.0 mg m^{-3} characterize the Washington coast as an area of higher coastal biomass than Oregon. This coast has a wider shelf that may contribute to greater tidal mixing, and more efficient nutrient recycling or retention of phytoplankton. A latitudinally more compact area of elevated summer chlorophyll concentrations immediately north of 44°N coincides with the widening of the 100 m bathymetric contour over Heceta Bank. Other regions of elevated chlorophyll along the entire Washington/Oregon/Northern California coastline also appear to be influenced by the widening of shelf bathymetry. Near 46°N, where the 200 m contour widens, chlorophyll concentrations > 4.0 mg m^{-3} appear to be sustained for a longer period of time than adjacent locations. As the 200 m contour retreats inshore, near 45°N, chlorophyll concentrations decrease. Widening of the 800 m contour near 42°N is associated with > 3.0 mg m^{-3} contour lines in 2000 and 2001. These results are consistent with previous examinations of interactions between bathymetry and chlorophyll distributions in the CCS [*Hill et al.*, 1998; *Pelaez and McGowan*, 1986]. The shelf immediately north and south of Heceta Bank is narrower (10-15 km wide) and, as shown in Figure 3.3, the chlorophyll cross-shelf extension of elevated chlorophyll is half that of the bank resulting in much lower chlorophyll concentrations over the same 60 km area.

A comparison of Figures 6a and 6b contrasts surface chlorophyll temporal variability at locations equidistant from the shore with those over similar bathymetric conditions, thus exploring the relationship between chlorophyll concentrations and changes in shelf width. Summer peaks in chlorophyll concentrations (Figure 3.5b) are consistently higher on Heceta Bank than the other two study sites. This comparison supports the pattern evident in Figure 3.3, which shows the average cross-shelf extension of the > 3.0 mg m^{-3} elevated chlorophyll isocline on Heceta Bank extending 35-55 km offshore (Figure 3.3). While at the northern and southern sites, where the shelf is narrower, a maximum cross-shelf extension of only 30 km from the coast is evident. These data suggest that the width of the shelf, bathymetry and the resulting cross-shelf extension of elevated chlorophyll along this portion of the Oregon coast make Heceta Bank a unique biological habitat.

Chapter 5

SUMMARY

Analysis of a four-year times series (1998-2001) of SeaWiFS chlorophyll data of the Oregon coast reveals a simple seasonal cycle of low chlorophyll concentrations from October through April, an increase in chlorophyll concentrations in the late spring and early summer (May-July) and maximum concentrations occurring in July on Heceta Bank and the southern site and August at the northern site. Concentrations are enhanced over Heceta Bank in spatial patterns that appear to mimic shelf bathymetry. Timing of the seasonal increase to summer higher chlorophyll concentrations varies with latitude, occurring first south of the bank in May-June, on the bank in June and finally north of the bank in June- early July. This pattern, as well as the seasonal pattern of SST, is consistent with latitudinal gradients in local wind forcing in the area, stronger south of the bank and decreasing with increasing latitude.

Interannual differences over the study period show the seasonal pattern of chlorophyll was strongest in 2001 and weakest in 1999, consistent with interannual differences in SST (coldest in 2001 and warmest in 1999). Although 1998 is considered an El Nino year, it is also a strong year for upwelling, therefore temperatures remained cooler than 1999 when Ekman transport was not as strong. In 2001 the duration of shelf intensified chlorophyll was the longest at all three locations and the greatest cross-shelf extensions of chlorophyll occurred on Heceta Bank and south of the bank. Cross-shelf maximum extension of chlorophyll occurred later in the summer season during the 1997-98 El Nino year on Heceta Bank and north of the bank. South of the bank, wind forcing

may have been strong enough to overcome the warmer spring temperatures attributed to El Nino to begin the seasonal elevation of chlorophyll in April.

Chlorophyll concentrations on Heceta Bank are positively correlated with areas north and south of the bank, however, the correlation between locations becomes insignificant when the distance is greater than 1° of latitude. The differences in the timing of chlorophyll concentrations in this region may be controlled by local bathymetry resulting in a decorrelation scale of 1° of latitude distance over an 8-day time period.

Results presented here also suggest shelf width affects the cross-shelf extent of chlorophyll off the Oregon coast. Elevated chlorophyll concentrations extend the farthest offshore over Heceta Bank, the widest part of the Oregon shelf. Monthly climatological data indicate Heceta Bank has higher summer chlorophyll peaks than on the shelf north and south of the bank. Interannually however, actual concentrations of chlorophyll at all three locations along the Oregon shelf do not appear to be influenced by the width of the shelf. Areas north and south of the bank equidistant from the coast as Heceta Bank, however, reveal the striking difference between chlorophyll concentrations on and off the bank. The shelf width of Heceta Bank results in higher concentrations of chlorophyll than regions to the north and south at an equal distance from the coast. The collective area over which elevated chlorophyll concentrations reside on the shelf over Heceta Bank is six times greater than the adjacent shelf regions.

The change in bathymetry over Heceta Bank causes chlorophyll patterns to behave differently from the rest of the surrounding coastline thus impacting the biological processes of the region. Possible explanations for this bathymetry-chlorophyll interaction include upwelled water more contact with bottom sediments rich in nutrients such as iron.

This study quantifies the seasonal cycle and the scope of interannual variability and relates elevated chlorophyll concentrations on Heceta Bank to bathymetry. Details of the dynamics controlling the patterns of surface chlorophyll on Heceta Bank, however, have not yet been adequately explained. Future research will establish the links between subsurface chlorophyll, temperature and nutrient structure as well as changes in physical forcing such as coastal jets and eddies and the surface patterns examined here.

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APPENDICES

Appendix A: Average Number of Valid Chlorophyll Returns in each Month

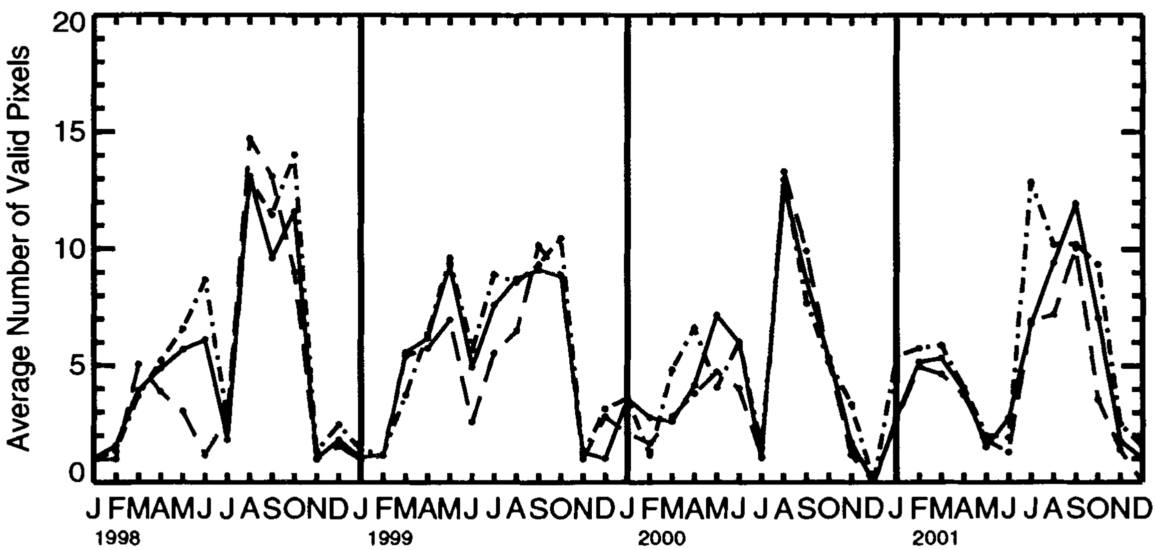


Figure A.1 - *Average Number of Valid Chlorophyll Returns*
Average number of valid daily chlorophyll returns within the 25x25 km box extracted from monthly composites at each study location (similar depths, 90-100m). The Heceta Bank box (blue solid line) is centered on 44.25 N, 124.38 W. The box south of the bank (red dashed-dotted line) is centered on 43.17 N, 124.55 W . The box north of the bank (green dashed line) is centered on 45.17 N, 124.14 W. A seasonal cycle in number of valid pixels is apparent with maximum numbers in the late summer-fall and minimum numbers in the winter.

Table B.1 - *Spatial and Temporal Standard Error Tables for Monthly 25x25 km box samples*

Spatial Standard Errors

	43N				44N				45N			
Month	**1998**	**1999**	**2000**	**2001**	**1998**	**1999**	**2000**	**2001**	**1998**	**1999**	**2000**	**2001**
1	0.228592	0.099307	0.074713	0.019772	0.05442	0.032462	0.021211	0.014685	0.767392	0.089697	0.03006	0.029273
2	0.015376	0.038585	0.03728	0.025162	0.017821	0.023674	0.029742	0.04156	0.036962	0.083306	0.027221	0.061163
3	0.043743	0.054599	0.01998	0.028709	0.021463	0.019405	0.038351	0.034997	0.025421	0.038322	0.066369	0.038676
4	0.036599	0.022072	0.031002	0.122612	0.00764	0.034798	0.038769	0.004472	0.035302	0.06921	0.068898	0.032776
5	0.074126	0.022485	0.032624	0.057248	0.008871	0.020371	0.006529	0.150441	0.042077	0.043151	0.035721	0.031525
6	0.092972	0.076015	0.023538	0.211817	0.012893	0.037449	0.029112	0.153035	0.057806	0.104519	0.027858	0.095562
7	0.147372	0.035342	0.374188	0.079633	0.195013	0.040601	0.213224	0.069008	0.121277	0.071037	0.096018	0.081961
8	0.084546	0.06453	0.069605	0.084271	0.057355	0.029548	0.058665	0.051019	0.12234	0.060621	0.095433	0.086422
9	0.052365	0.068858	0.056415	0.042197	0.057714	0.065694	0.040381	0.06065	0.052192	0.072583	0.058699	0.069589
10	0.024047	0.017505	0.056074	0.050185	0.011905	0.031691	0.046237	0.051824	0.039343	0.02812	0.057619	0.131225
11	0.117307	0.14044	0.050347	0.059349	0.09475	0.073902	0.017666	0.083878	0.046782	0.021979	0.042446	0.048032
12	0.124869	0.019135	NA	0.089084	0.032741	0.028994	NA	0.07506	0.050854	0.067139	NA	NA

Temporal Standard Errors

	43N				44N				45N			
Month	**1998**	**1999**	**2000**	**2001**	**1998**	**1999**	**2000**	**2001**	**1998**	**1999**	**2000**	**2001**
1	4.07824	0.161953	0.227444	0.119934	0.264776	0.445762	0.313456	0.143632	3.19528	NA	0.378295	0.252222
2	0.291517	0.147985	0.153547	0.525482	0.417843	0.269371	0.30125	0.183877	NA	0.25878	0.171916	0.631073
3	0.313414	0.159077	0.6593	0.600134	0.363182	0.29705	0.179499	0.179378	0.274147	0.121341	0.761769	0.579736
4	0.092809	0.263165	0.409893	0.145119	0.15271	0.242352	0.221592	0.710801	0.38478	0.516617	1.39127	0.270283
5	0.199152	0.230378	0.096258	2.24545	0.56312	0.259133	0.230233	0.827634	0.349583	0.364014	0.444018	0.132082
6	0.194145	0.734933	0.30605	0.697821	0.697387	0.724112	0.48463	2.80212	0.918738	0.899895	0.260971	0.017613
7	2.11184	0.61833	0.890105	1.43932	1.62583	0.313685	1.13398	1.13168	2.49647	0.626578	0.757522	1.21691
8	0.715469	0.439522	0.570192	0.853551	0.63924	0.480078	0.774257	0.709803	0.438397	0.665652	0.840191	0.975132
9	0.767605	0.834233	0.468866	0.745538	0.676446	0.629655	0.848592	0.304552	0.439764	0.774314	0.333584	1.58577
10	0.192685	0.752867	0.932717	0.227937	0.165669	0.13452	1.76061	0.25806	0.236623	1.49653	0.668681	0.432858
11	0.361896	0.179812	0.180383	1.34439	0.66287	0.498326	0.34255	0.602793	0.228224	NA	1.44025	0.305628
12	0.133539	0.193379	NA	0.120718	0.539436	0.285672	NA	0.172035	0.390856	0.505589	NA	NA

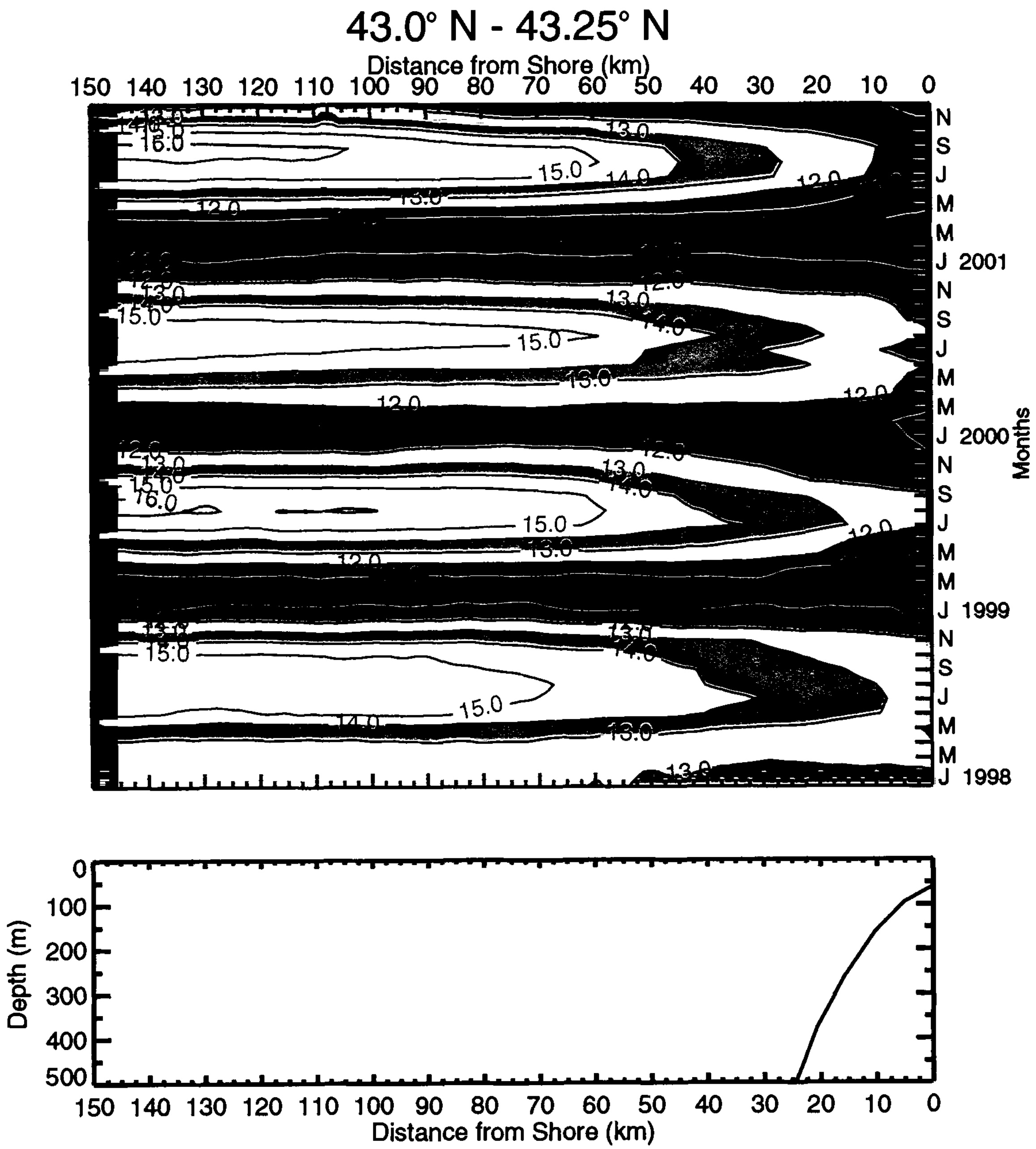


Figure C.1 - *Monthly Sea Surface Temperature Contours, 43.0-43.25oN*

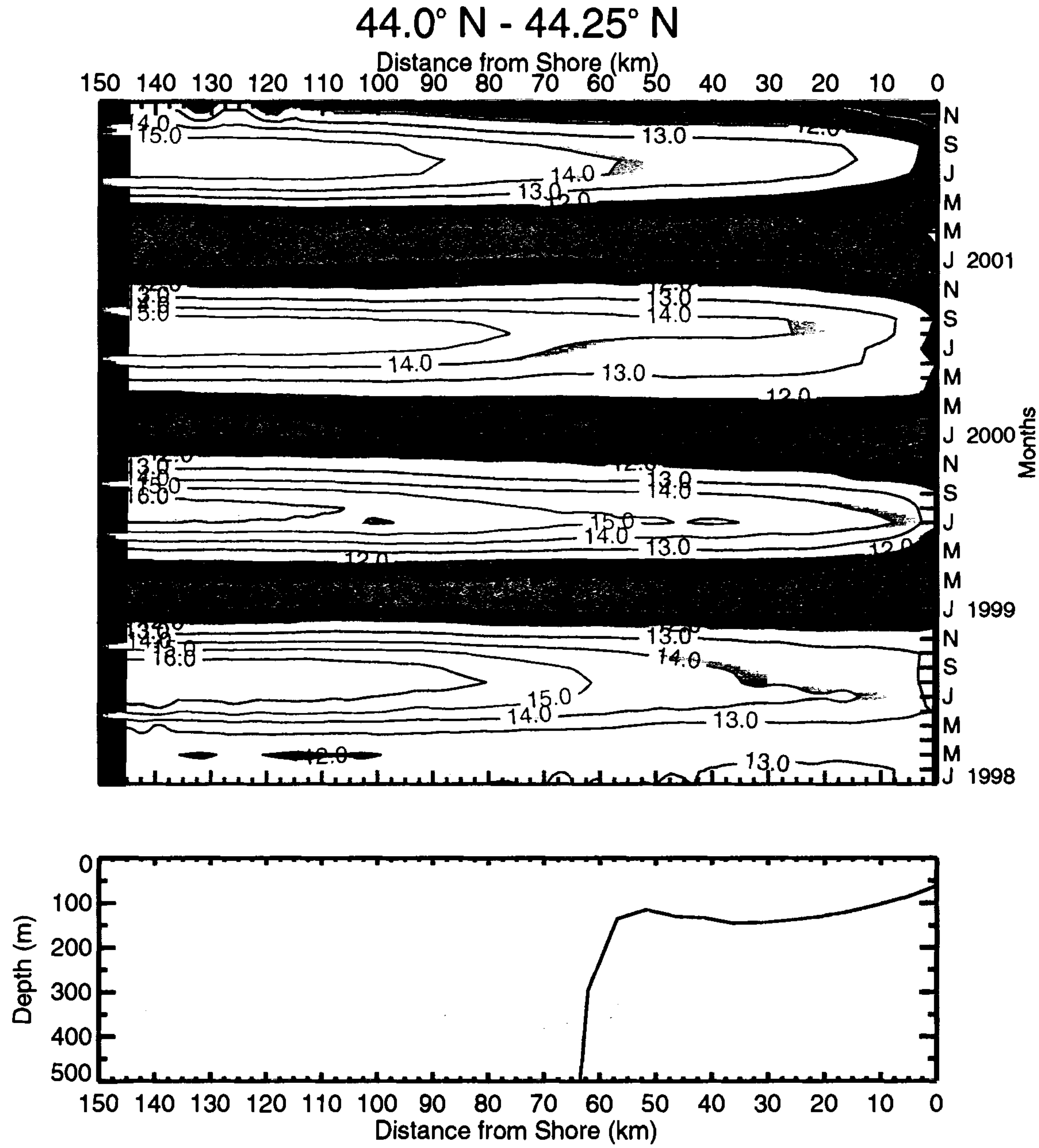


Figure C.2 - *Monthly Sea Surface Temperature Contours, 44.0-44.25oN*

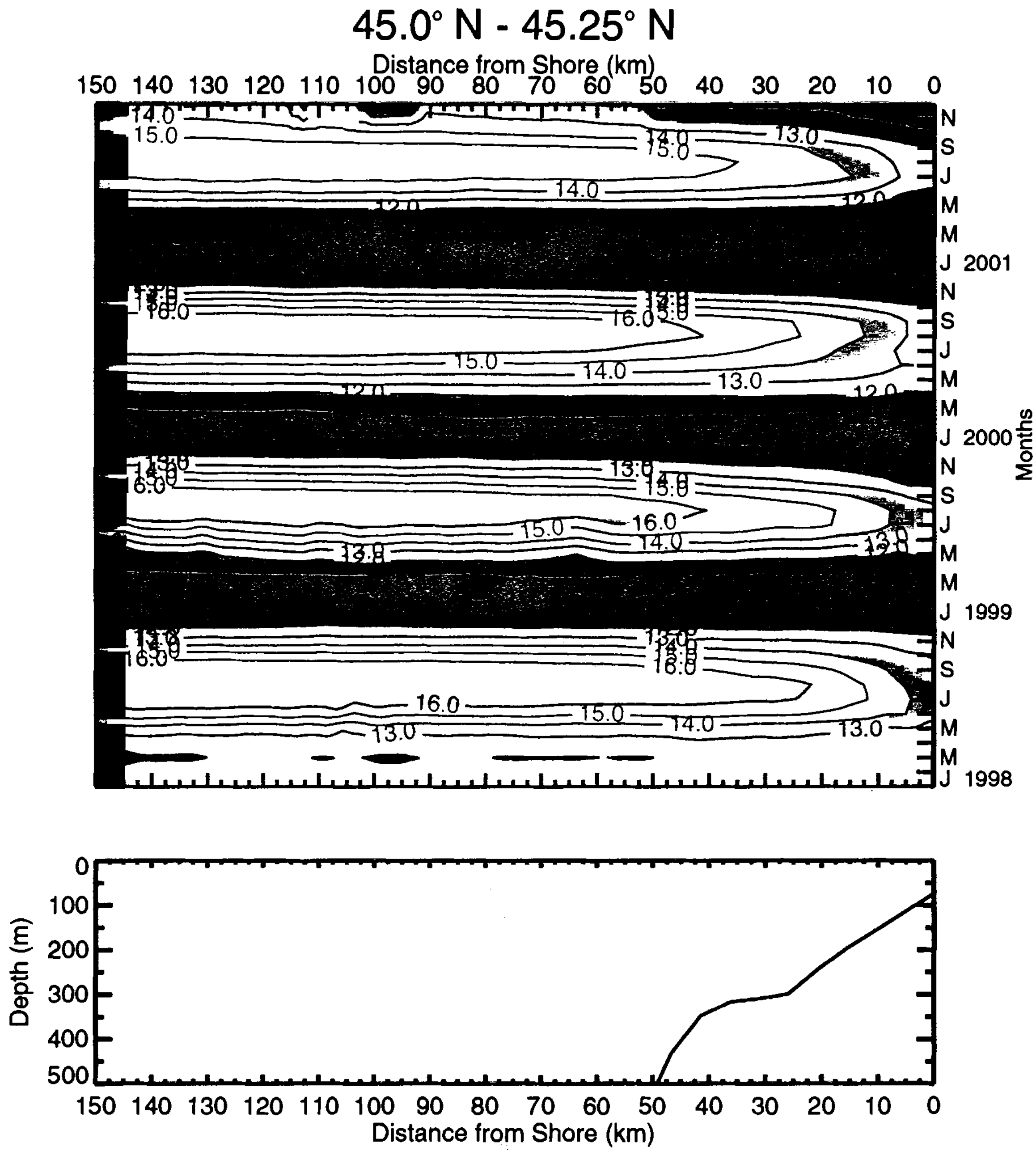


Figure C.3 - *Monthly Sea Surface Temperature Contours, 45.0-45.25°N*

Appendix D: Monthly Temperature Derived Upwelling Index Contours

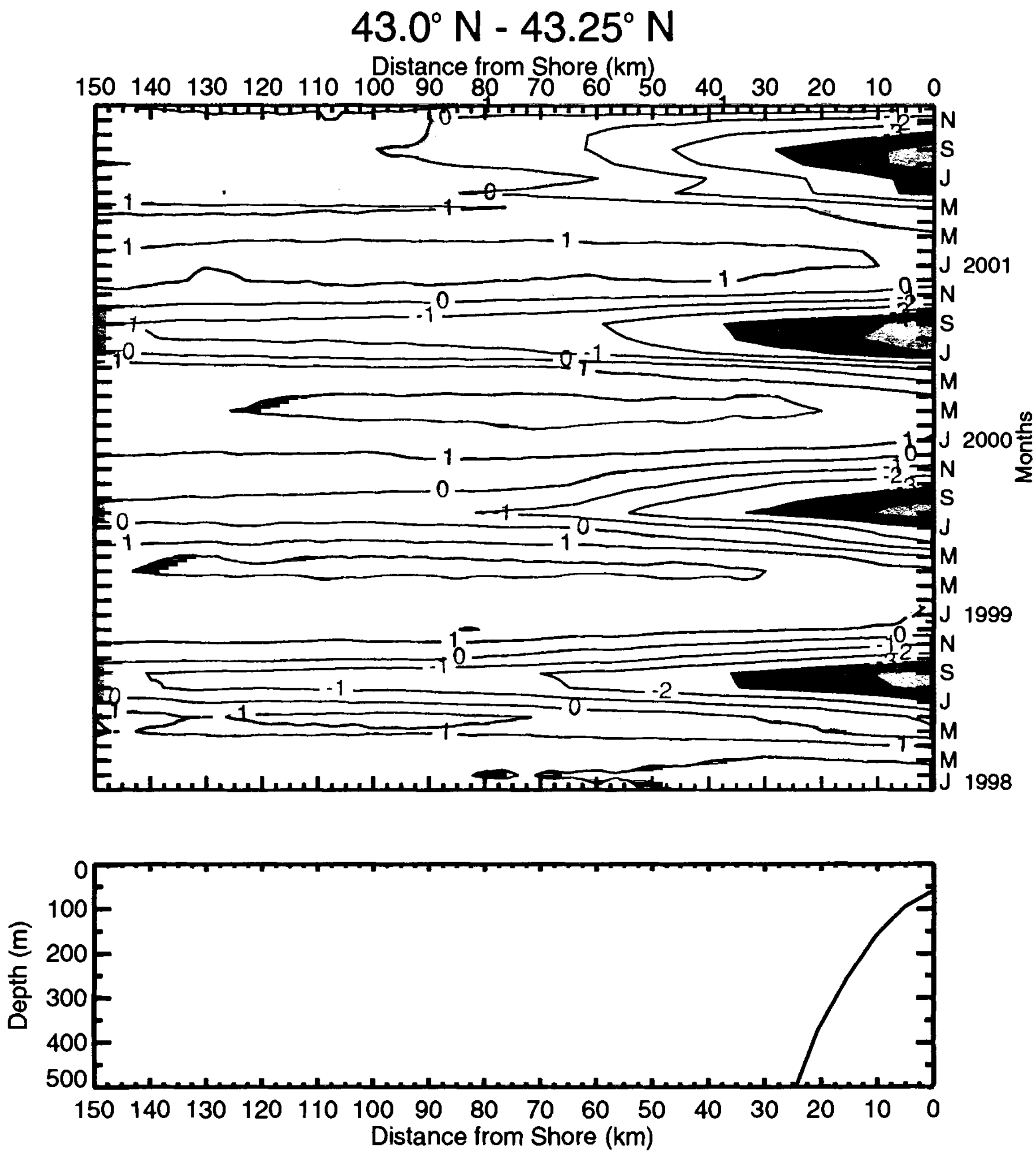


Figure D.1 - *Monthly Temperature Derived Upwelling Index Contours, 43.0-43.25°N*

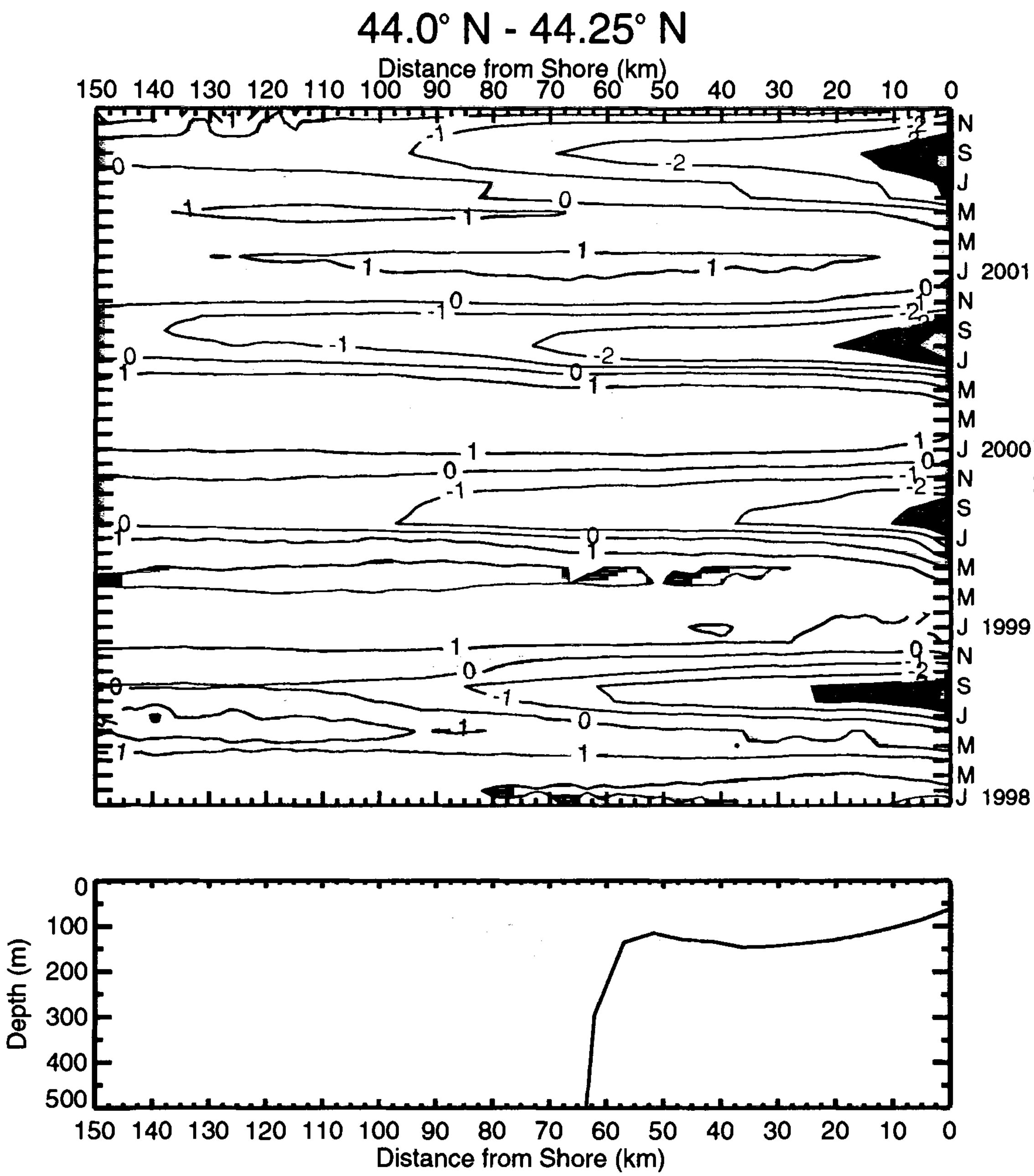


Figure D.2 - *Monthly Temperature Derived Upwelling Index Contours, 44.0-44.25ºN*

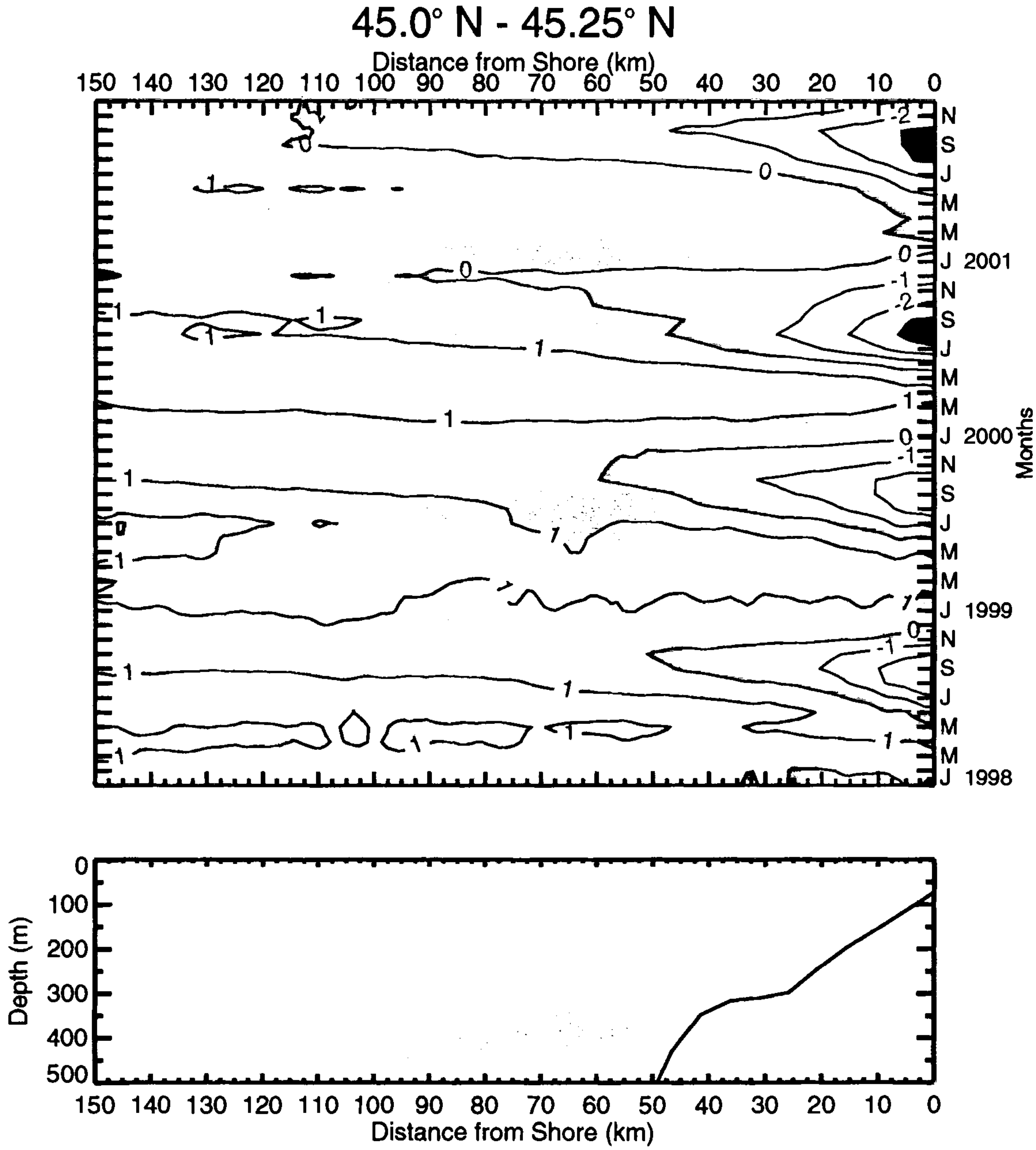


Figure D.3 - *Monthly Temperature Derived Upwelling Index Contours, 45.0-45.25ºN*

Appendix E: Influence of the Columbia River Plume

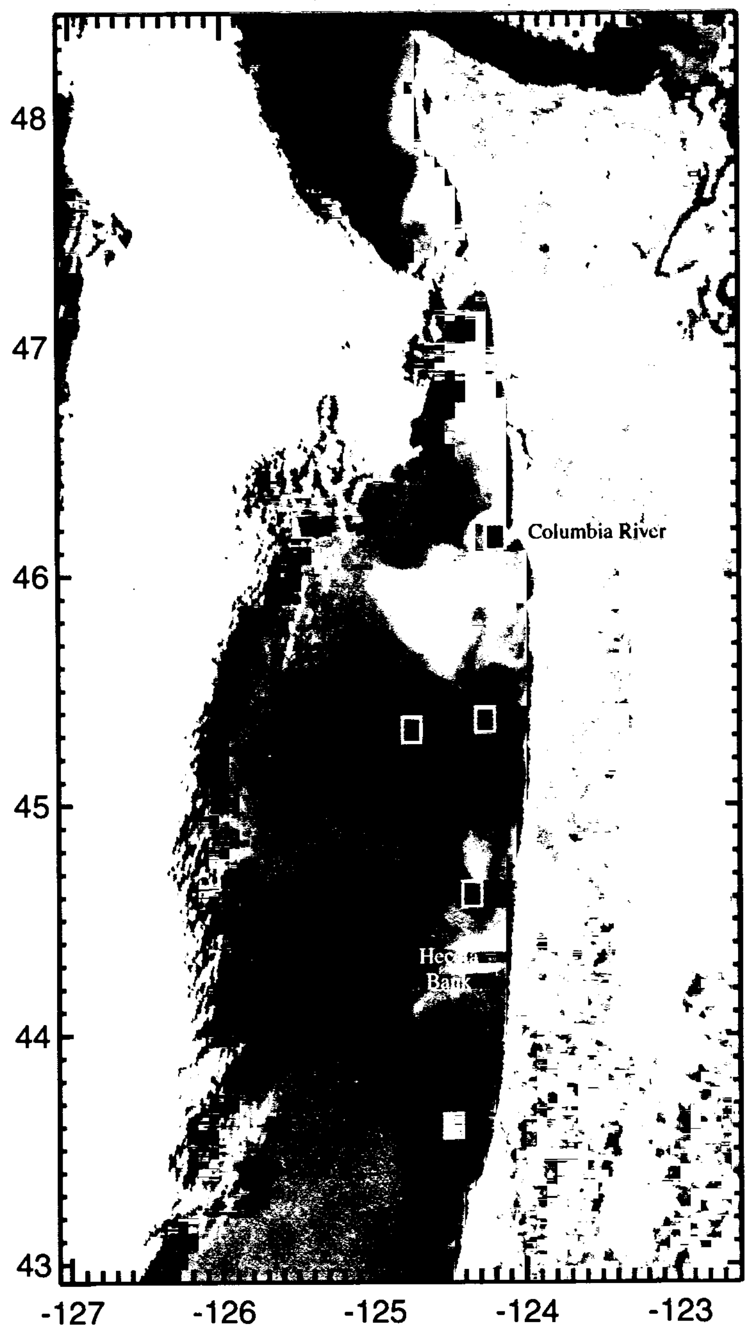
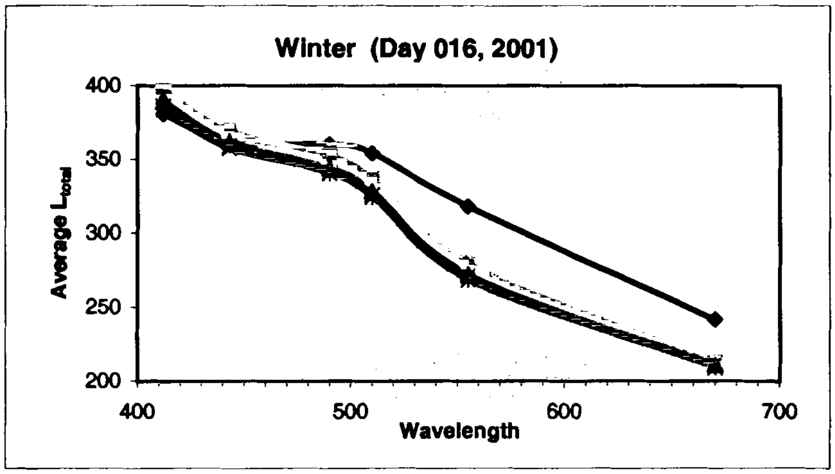
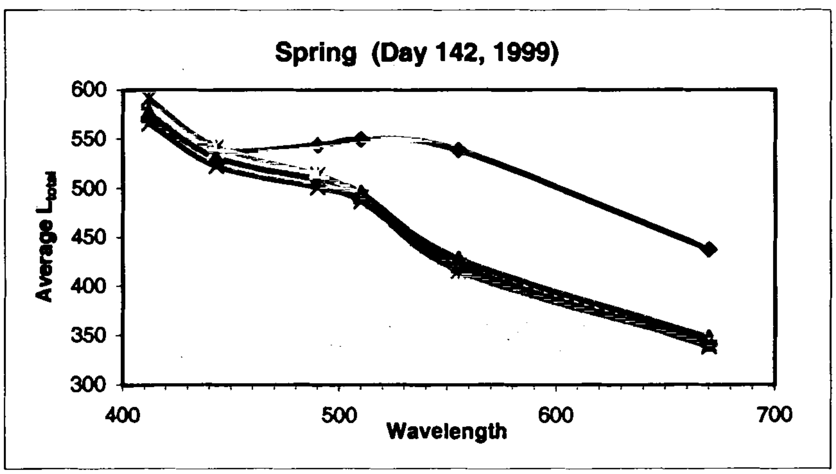


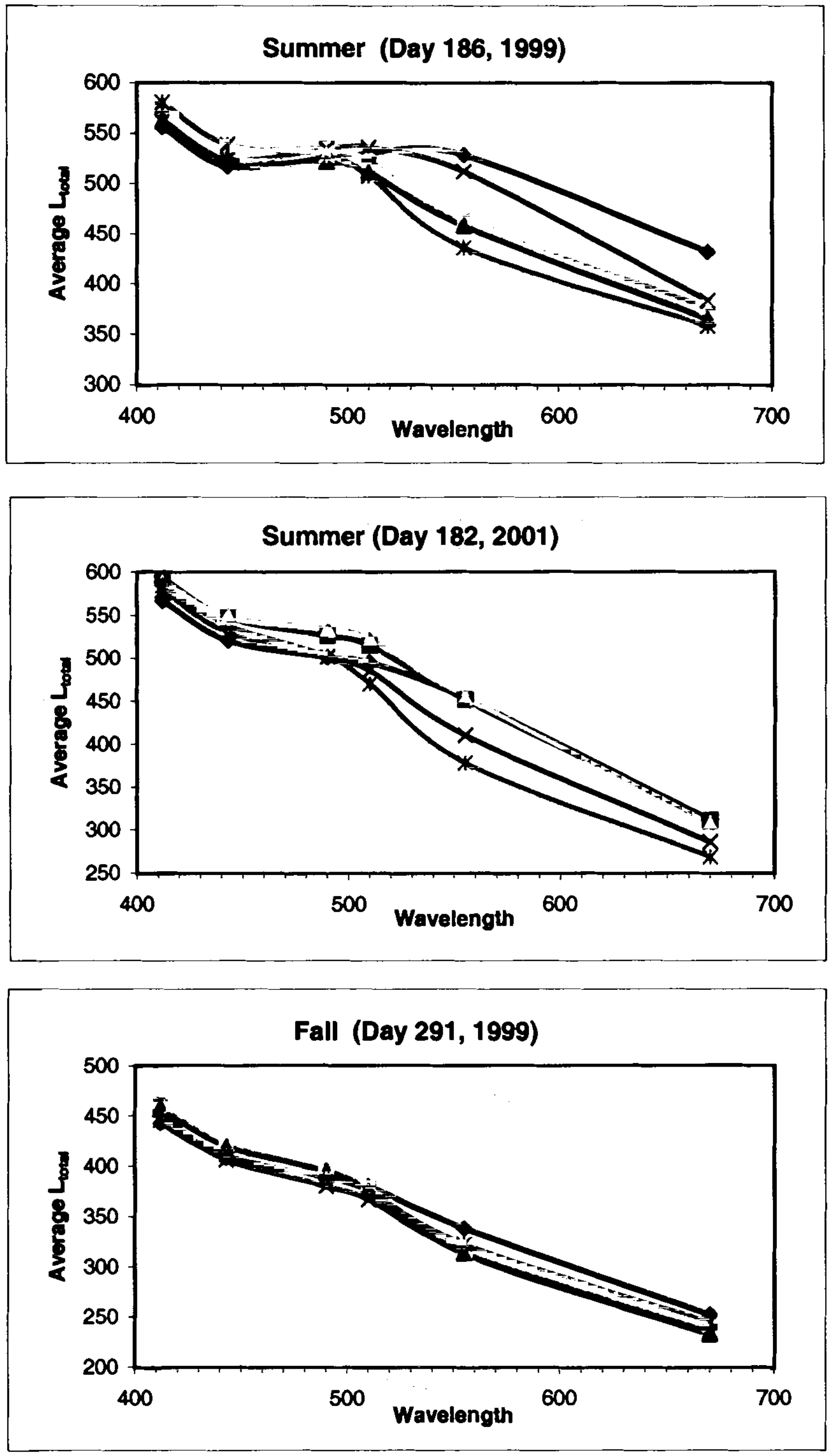
Figure E.1 - *Total Water Leaving Radiance, Day 142, 1999*





Lines are color coded to boxes marked Figure E.1

Figure E.2 - *Total Water Leaving Radiance Spectra at 5 Locations*



Lines are color coded to boxes marked on Figure E.1

Figure E.2 Continued

Appendix F: Daily Autocorrelations 1998

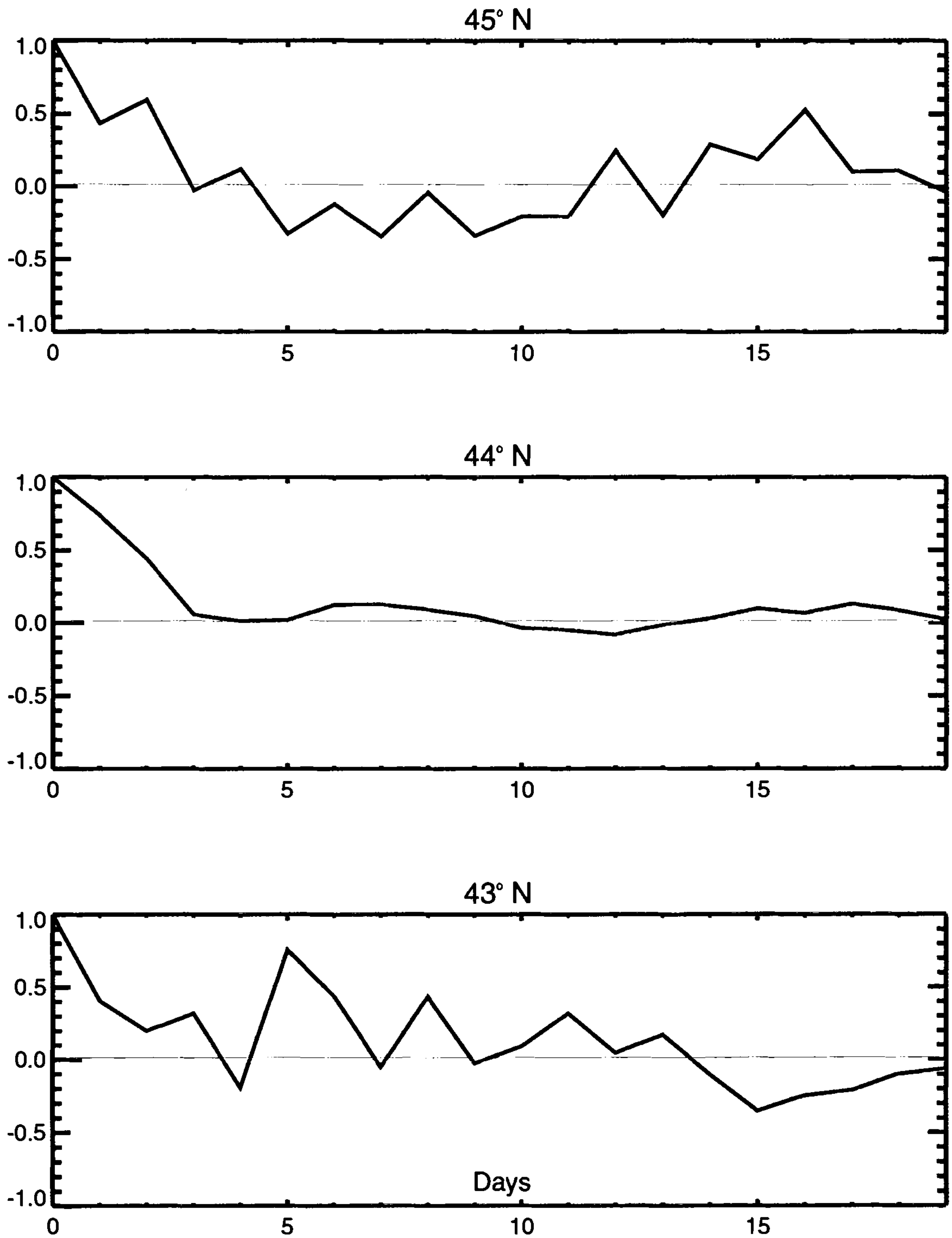


Figure F.1 - *Daily Chlorophyll Autocorrelations 1998*

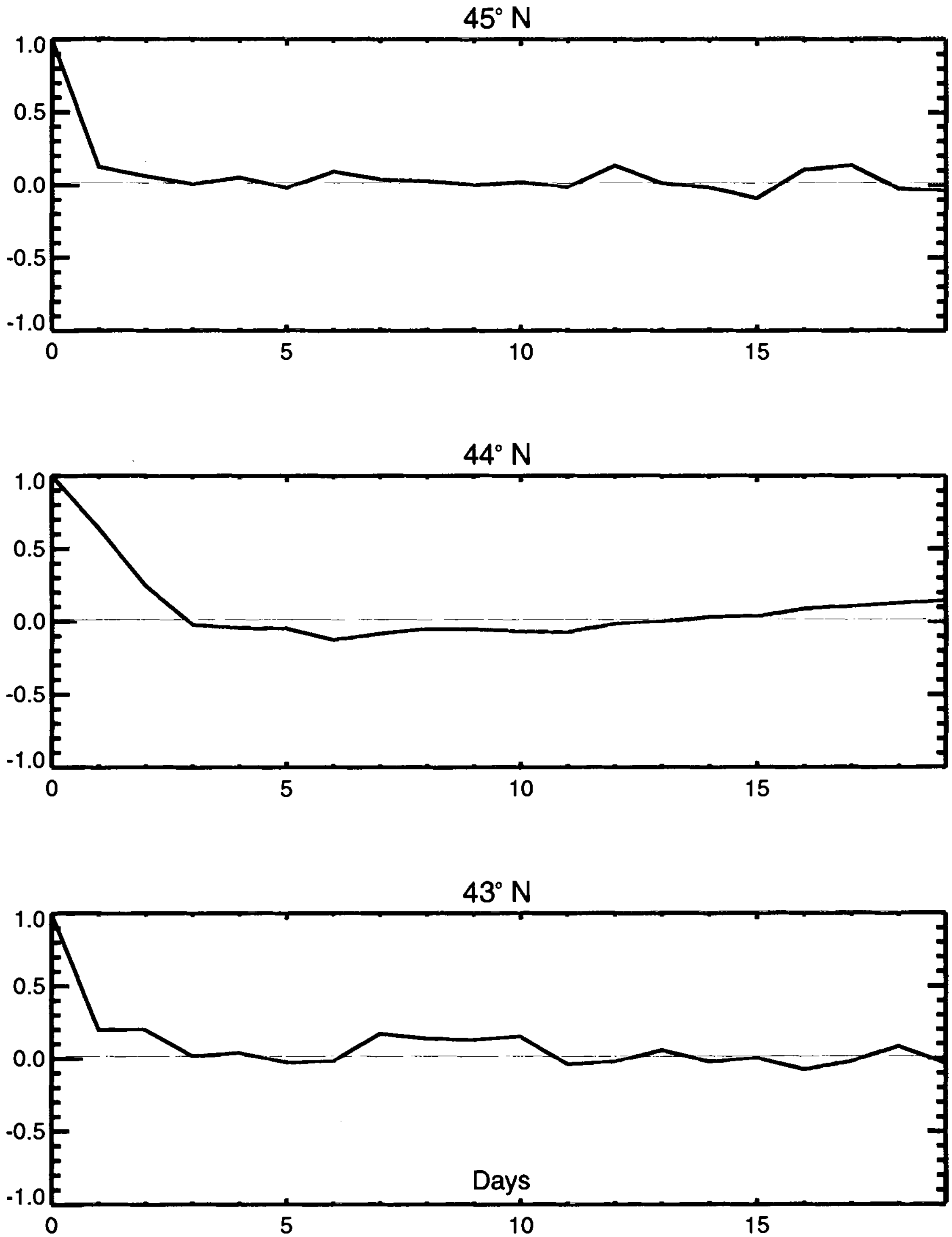


Figure F.2 - *Daily SST Autocorrelations 1998*

Appendix G: 8-Day Chlorophyll Composites with SST Gradients

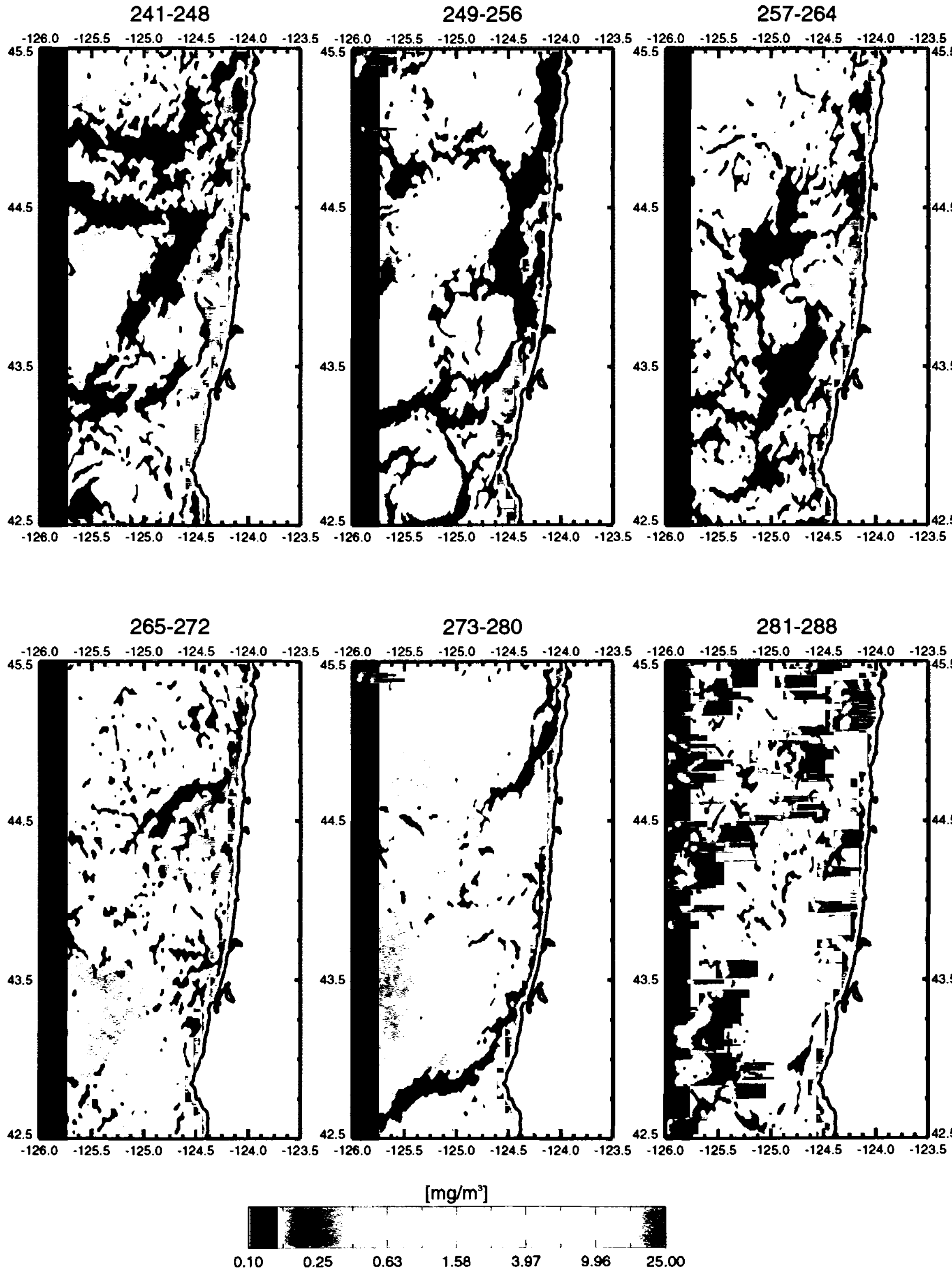


Figure G.1 - *8-Day Chlorophyll Composites with SST GRadients 1998*

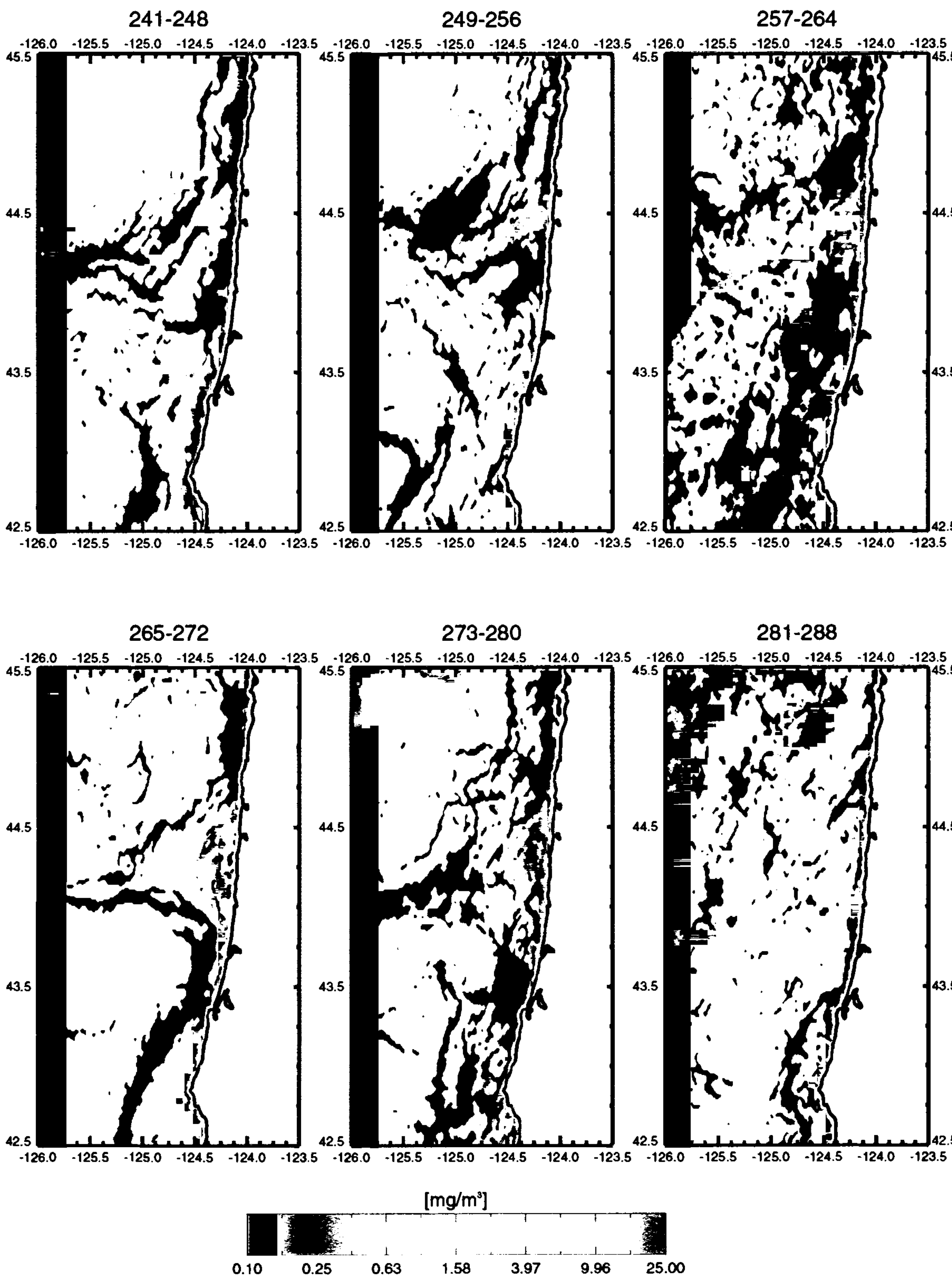


Figure G.2 - *8-Day Chlorophyll Composites with SST Gradients 1999*

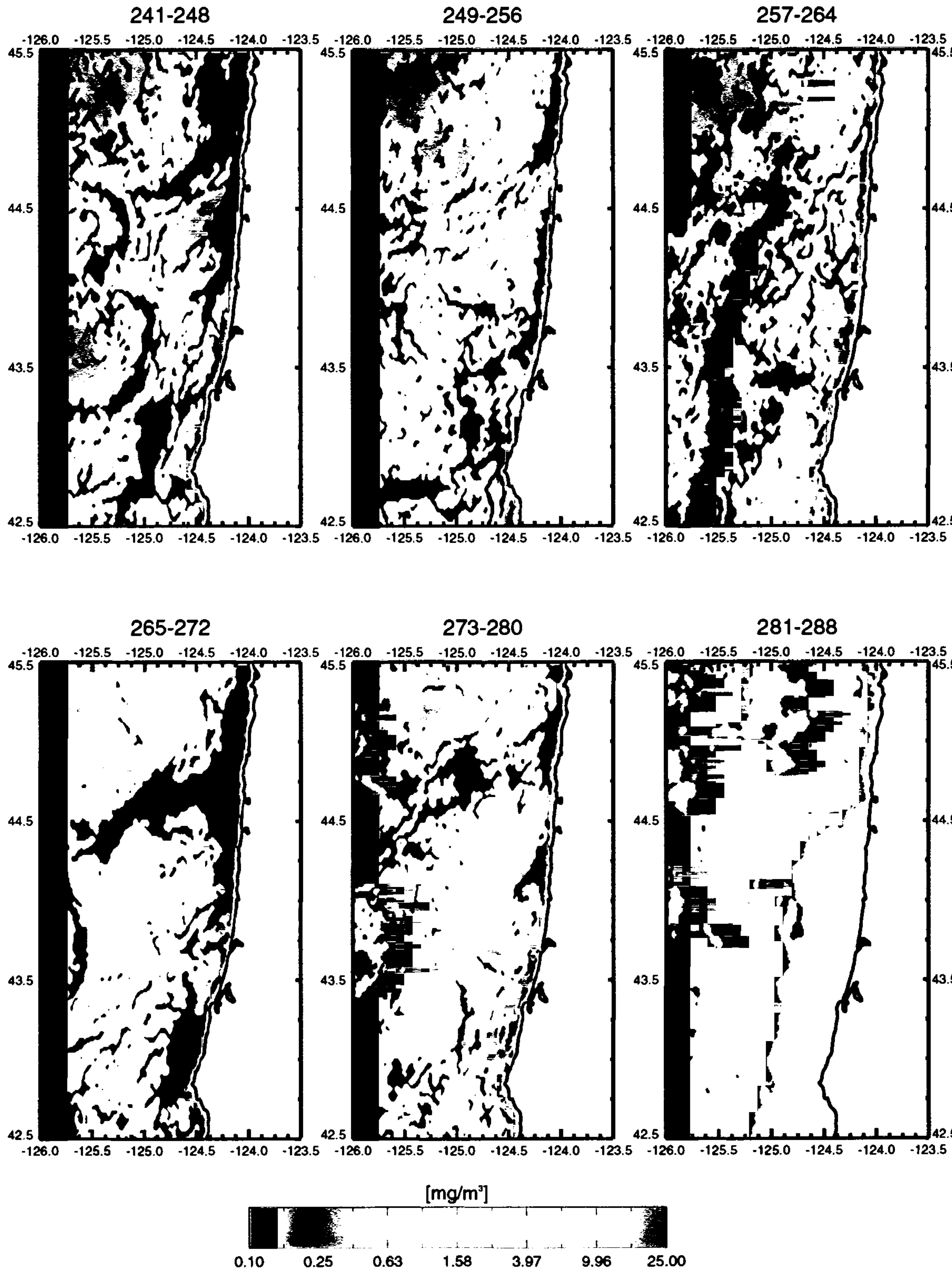


Figure G.3 - *8-Day Chlorophyll Composites with SST Gradients 2000*

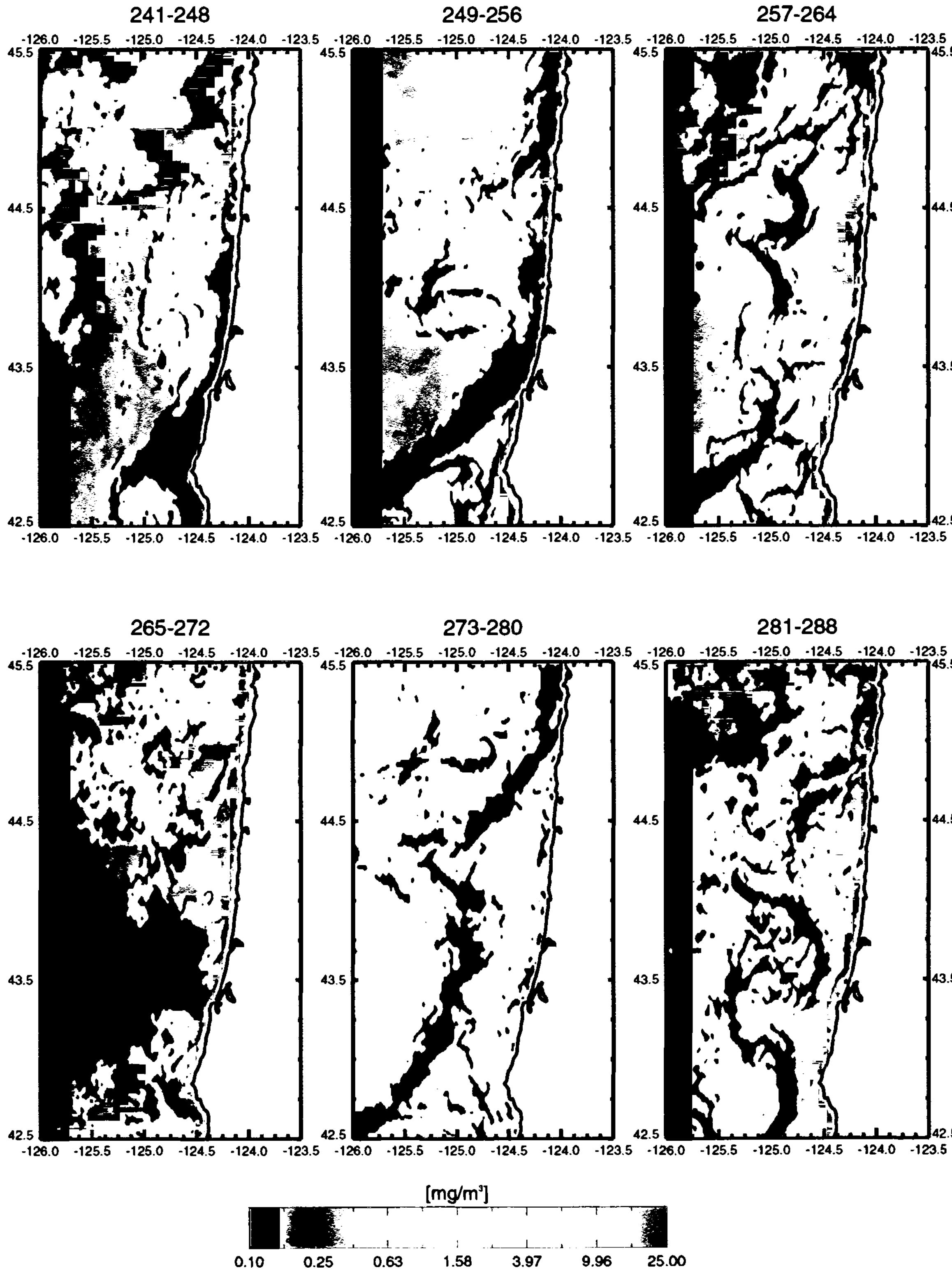


Figure G.4 - *8-Day Chlorophyll Composites with SST Gradients 2001*

Appendix H: Monthly SST verses Chlorophyll

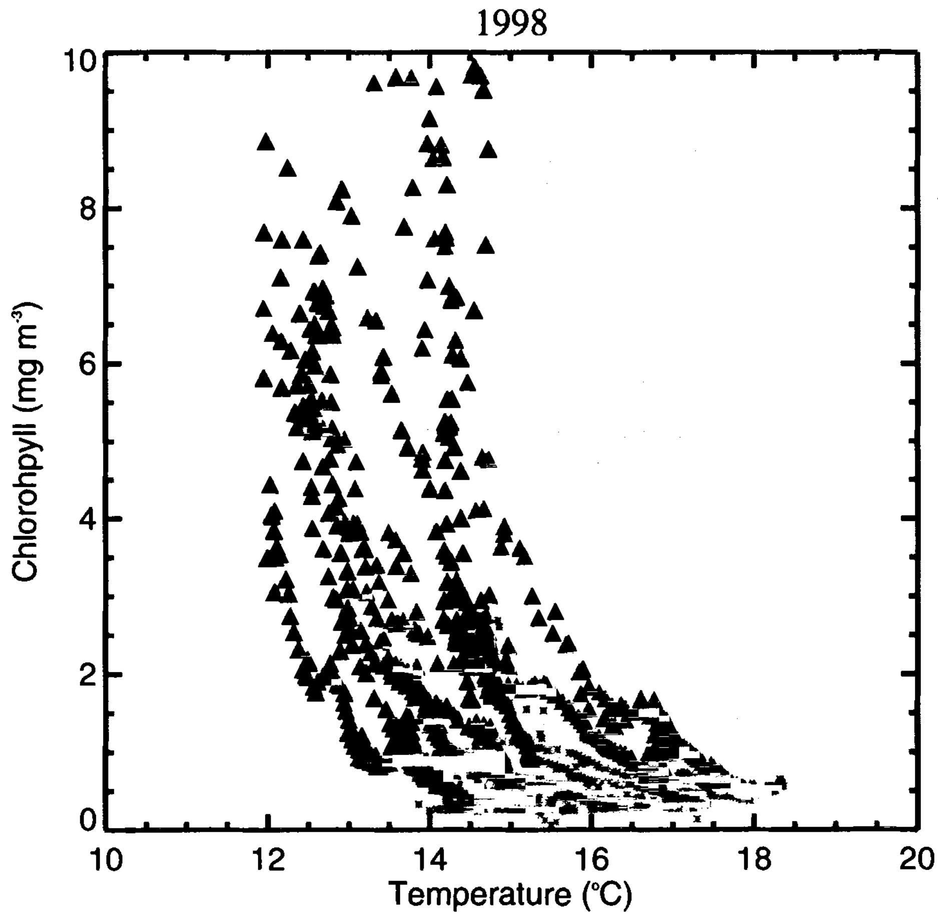


Figure H.1 - *Monthly SST verses Chlorophyll 1998*

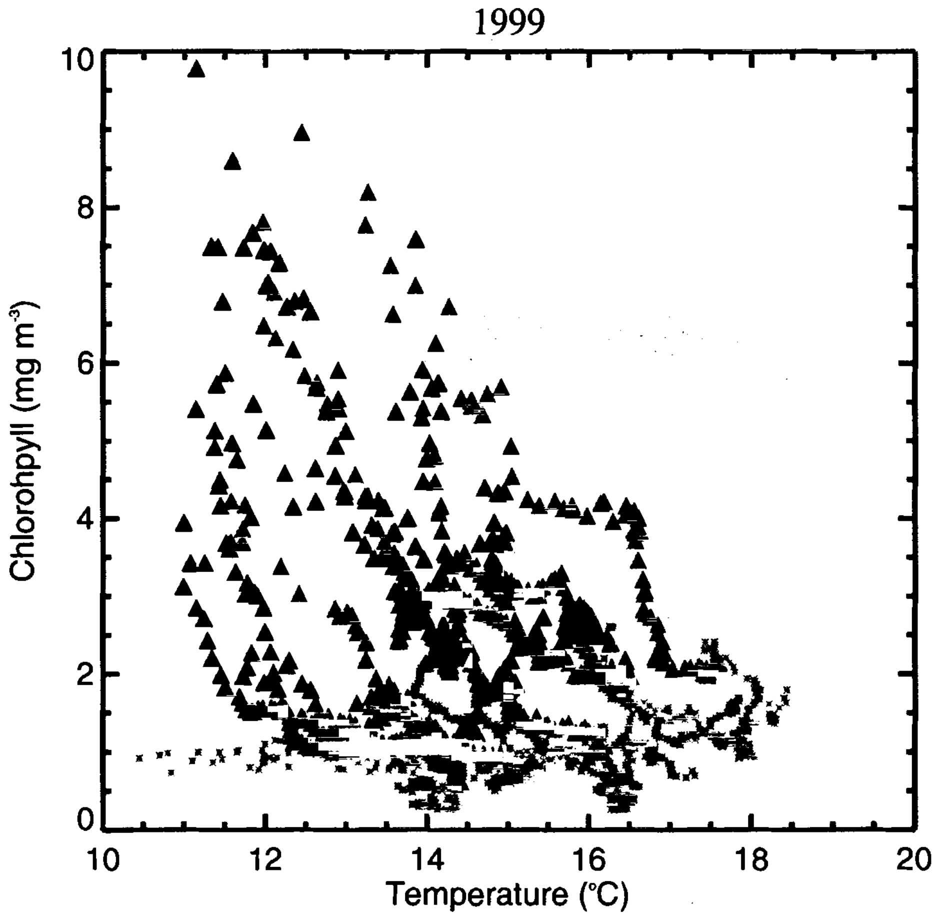


Figure H.2 - *Monthly SST verses Chlorophyll 1999*

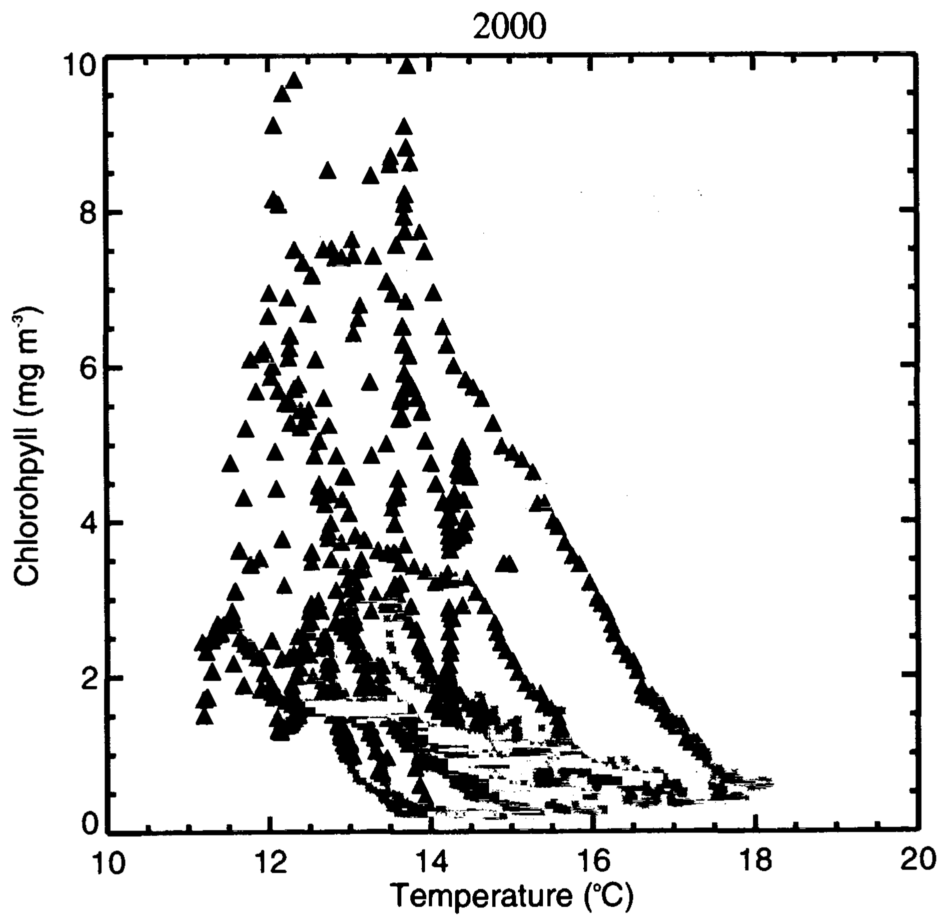


Figure H.3 - *Monthly SST verses Chlorophyll 2000*

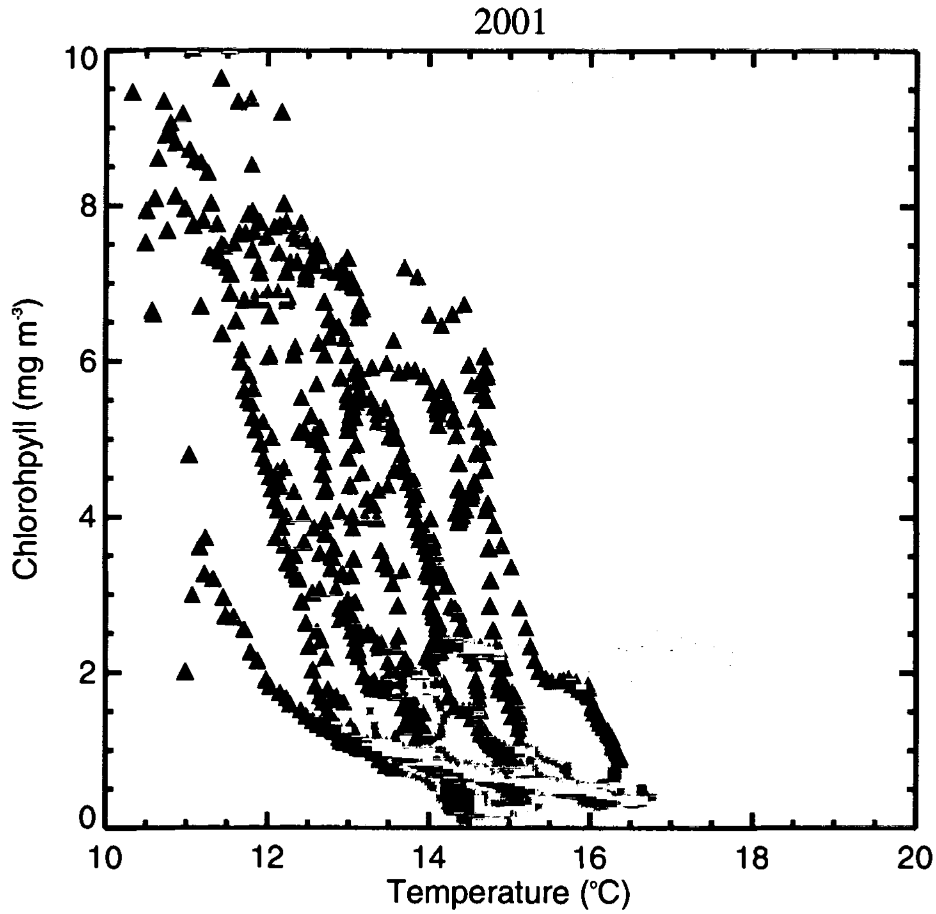


Figure H.4 - *Monthly SST verses Chlorophyll 2001*

BIOGRAPHY OF THE AUTHOR

Jennifer Bosch was born in Teaneck, New Jersey on August 3, 1977. She was raised in Essex Fells, New Jersey and graduated from West Essex Regional High School in 1995. She attended Cook College, Rutgers University and graduated in January of 2000 with a Bachelor's degree in Environmental Science and Natural Resource Management. She moved to Maine in August of 2000 to enter the Oceanography graduate program at The University of Maine.

After receiving her degree, Jennifer will be pursuing a job in the marine sciences field. Jennifer is a candidate for the Master of Science degree in Oceanography from The University of Maine in December, 2002.