THE TRANSPORT AND DISTRIBUTION OF THE TOXIC DIATOM *PSEUDO-NITZSCHIA* SPP. IN THE COOS BAY ESTUARY AND THE ADJACENT CONTINENTAL SHELF

by

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"The Transport and Distribution of the Toxic Diatom *Pseudo-nitzschia* spp. in the Coos Bay Estuary and the Adjacent Continental Shelf," a thesis prepared by Christopher A. Cziesla in partial fulfillment of the requirements for the Master of Science degree in the Department of Biology. This thesis has been approved and accepted by:

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Dr. Alan Shanks

Along the Oregon coast blooms of *Pseudo-nitzschia* spp. have been an almost annual occurrence since monitoring began in the late 80's. This study looks at the distribution of *Pseudo-nitzschia* spp., in relation to meteorological and oceanographic conditions. A series of transects (1995-98) were done in Coos Bay and over the adjacent continental shelf under a variety of oceanographic conditions. An intense sampling program was undertaken in June 1998, with simultaneous nearshore and in bay (Coos Bay) sampling, including a nearshore grid, 24 hour anchor station in the bay, and an in bay incoming tide drift study.

The results suggest that blooms develop nearshore after upwelling events. In conditions of relaxed upwelling highest cell concentrations were found immediately adjacent to the coast in surface and mid-depth waters. At stations in Coos Bay, *Pseudo-nitzschia* spp. concentrations increased with the incoming tide. Nearshore phytoplankton populations were transported into the bay, initially in the more saline bottom waters, but were rapidly mixed throughout the water column by the turbulent flow in the channels. On ebbing tides there was a reduced number of phytoplankton in the water column, possibly indicating consumption by in bay filter feeders or sinking and deposition on the bottom.

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CHAPTER I

GENERAL INTRODUCTION

Over the past several decades the number of documented harmful algal blooms (HAB's) has increased dramatically. A number of mechanisms have been suggested to explain this apparent increase including; a) natural dispersal by currents, storms and other mechanisms, b) nutrient enrichment of coastal waters from anthropogenic sources including agriculture and aquaculture, c) transport by ships ballast water of harmful algal innocula, d) long term climatic trends in temperature or wind, and e) increased scientific scrutiny by more scientists using better detection methods (Anderson, 1997). The economic impacts associated with HAB's are far reaching, affecting diverse industries from commercial fisheries to tourism and recreation (Habas and Gilbert, 1974). In order to protect the public and minimize the detrimental effects of HAB's emphasis has been placed on developing effective monitoring programs. Current monitoring varies from locality to locality, but primarily consists of testing shellfish tissue for elevated levels of toxins. If dangerous levels are found, warnings are issued and harvesting is restricted. The state of Oregon currently monitors six sites two times per month for elevated levels of domoic acid, the neurotoxin responsible for Amnesic Shellfish Poisoning (ASP). If domoic acid levels exceed 20 ppm, recreational and commercial harvesting of shellfish is restricted. The turn around time between sampling and harvesting closures can be in excess of a week, potentially leaving the public at risk. The development of a monitoring system which aims to predict when shellfish are likely to become toxic would help reduce the risk of public exposure and potentially limit the economic impacts of HAB's.

Due to the relatively limited understanding of the ecology and oceanography of HAB's the National Science Foundation and the National Oceanic and Atmospheric Administration sponsored a workshop to develop a national research agenda. The goal of this program is "To develop an understanding of the population dynamics and the trophic impacts of harmful algal species which can be used as a basis for minimizing their adverse effects on the economy, public health, and marine ecosystems". With the national research plan and current state monitoring as a backdrop, the focus of this study was to determine the transport and distribution of the diatom *Pseudo-nitzschia* spp., the causative organism for ASP, in the Coos Bay estuary and the adjacent continental shelf. The study has been divided into two sections, the first, focusing on the continental shelf near the mouth of Coos Bay, Oregon, investigating the location of *Pseudo-nitzschia* spp. under various meteorological and oceanographic conditions. The second section focused on the transport and distribution of *Pseudo-nitzschia* spp. within the Coos Bay estuary.

CHAPTER II

SPATIAL DISTRIBUTION OF THE TOXIC DIATOM *PSEUDO-NITZSCHIA* SPP. OVER THE CONTINENTAL SHELF ADJACENT TO COOS BAY, OREGON

Introduction

Blooms of the pennate diatom *Pseudo-nitzschia* spp. have been documented on both coasts of North America. In 1987, in the waters of Cardigan Bay, Prince Edward Island, Canada, a bloom of *Pseudo-nitzschia multiseries* , (previously known as *Nitzschia pungens* Grunow f. *multiseries* Hasle) resulted in 3 human fatalities and over 100 cases of acute intoxication after the ingestion of cultured blue mussels (*Mytilis edulis*) which had concentrated domoic acid (Bates, 1989). Domoic acid is a naturally occurring amino acid and neurotoxin that is produced by some seaweeds (Takemoto, 1958) and a few diatom species (Subba Rao, 1988). On the West Coast in September of 1991, a bloom of *Pseudo-nitzschia australis* was implicated in the death of brown pelicans and Brandt's cormorants in Monterey Bay, California (Work, 1993). Later that year domoic acid was discovered in razor clams and dungeness crabs from Oregon and Washington, resulting in the closure of both commercial and recreational fisheries (Wood & Shapiro, 1993). In 1997, domoic acid was found to have caused the death of about 80 California Sea Lions in Monterey Bay, California. Additional restrictions on shellfish harvests have occurred along the Oregon and Washington coast during the spring and summer months of 1997-1999.

The historical occurrence of *Pseudo-nitzschia spp.* (1920-1996), along the West Coast of the United States, has been summarized by Fryxell et al. (1997). *Pseudo-nitzschia* spp. appears to have been a relatively common constituent of the coastal phytoplankton assemblage throughout that period. Highest concentrations have been reported during the spring through fall during the upwelling period on the West Coast. In these waters, there are at least seven diatom species known to produce domoic acid (*Pseudo-nitzschia australis, P. multiseries, P. delicatissima, P. seriata, P. pungens, P. turgidula, and P. pseudodelicatissima*). As more species are tested, there will undoubtedly be additional domoic acid producers reported.

The population dynamics of *Pseudo-nitzschia* spp. and the physical and chemical characteristics of the water column supporting blooms of these species are poorly understood. Although there are several theories as to the environmental conditions that contribute to domoic acid production, it appears that *Pseudo-nitzschia* spp. produce domoic acid in conditions of nutrient stress after the cessation of cell division. In the species *P. pungens* domoic acid production has been attributed to silica limitation in the presence of abundant nitrogen (Bates, 1991). Additional studies have also indicated that domoic acid production was enhanced by a factor of ~3 by phosphate limitation (Pan, 1996)..

In response to the domoic acid outbreaks on the West Coast, Oregon Sea Grant sponsored a workshop at the University of Oregon Institute of Marine Biology in February of 1992. This workshop identified several priorities for scientific research. A highlighted priority was the need for shellfish and phytoplankton monitoring programs in order to detect the "[correlations] between oceanographic conditions, phytoplankton, and shellfish in regard to the spatial and temporal distribution of domoic acid in the coastal environment. Such an integrated program may lead to a comprehensive monitoring system that would provide shellfish harvesters, growers, and regulators with early warnings of potential domoic acid events" (Wood & Shapiro, 1993). In recent years *Pseudo-nitzschia* spp. blooms have occurred regularly in the waters off Oregon and Washington (Horner, 1997; Hughes, 1997). In samples taken during the fall of 1995-1997 high concentrations of *Pseudo-nitzschia* spp. were found on the pycnocline or associated with an upwelling front (Shanks, unpub. observ.) In June 1997 high concentrations of *Pseudo-nitzschia* spp. were again found in samples collected from the NOAA ship McArthur in the nearshore ocean waters off the mouth of Coos Bay, Oregon (unpub. data). The research presented below attempts to determine the distribution of *Pseudo-nitzschia* spp. over the continental shelf adjacent to Coos Bay, Oregon under various meteorological and oceanographic conditions.

Coastal Oregon Upwelling and Oceanography

The upwelling system along the Oregon coast has been studied and described extensively during the last 25 years. Early work includes that by Smith (1966) and Huyer (1975, 1976) while additional details have been contributed by Halpern (1976), Mooers et al. (1976), Peterson et al. (1979), and Small and Menzies (1981) among others. The general description put forth by these works is as follows. Along the West Coast of North America winds can be described as monsoonal, with a winter rainy season (October - March) during which winds are predominantly from the southwest. The upwelling season begins in April or May, with winds from the northwest. Under northwesterly wind stress, Ekman transport of the surface layer of the water column, up to 20 m thick, is directed offshore. The offshore transport of warm surface water is balanced by the onshore transport of deep (100 - 200 m depth) cold waters from a distance of 20 - 30 km offshore. The upwelled water is dense (cold and saline) and rich in nitrate, silicate, and phosphate.

The state of upwelling can be defined by the position of the permanent pycnocline (25.5 - 26.0 sigma-t). During active upwelling, the permanent pycnocline intersects the sea surface about 10 km offshore (Collins, 1964). Active upwelling occurs when winds blow more or less continuously from the northwest and is graphically illustrated by hydrographic sections in which isotherms, isohalines, and isopycnals slope upward toward shore. The extent of offshore transport of surface waters is limited by a pressure gradient toward shore that is developed shortly after the beginning of an upwelling event. The Columbia River plume, located about 25 - 55 km offshore, acts as a low density surface barrier, that restricts further offshore surface flow (Peterson, 1979).

When the upwelling favorable winds taper off, or reverse to southwesterly, offshore surface waters move back towards shore and the permanent pycnocline becomes more horizontal and no longer intersects the sea surface. This condition is referred to as relaxed upwelling and can alternate with upwelling events on a time scale of one to three days (Halpern, 1976). Small (1973) suggested the transient state of rapid relaxation of upwelling might be the condition under which the highest rates of primary production occur. Less intense winds during relaxation events presumably allow phytoplankton cells longer residence times near the surface in the photic zone for more effective utilization of nutrients made available by recent and localized upwelling. Huntsman and Barber (1977), evoked a similar mechanism and reported that weak upwelling, rather than strong upwelling, was responsible for the most productive conditions off northwest Africa.

Reduced wind stress during summer allows the formation of a seasonal mixed layer and associated pycnocline at 10 - 20 m depth. This shallower pycnocline is formed by the seasonal thermocline and a halocline derived from water associated with the Columbia River plume (Mooers et al., 1976). The density of this feature is 24.0 - 24.5 sigma-t and is nearly horizontal. However, during active upwelling the seasonal pycnocline often merges with the permanent pycnocline to form a surface front about 10 km offshore.

The dynamics of the innershelf region (0 - 10 km offshore) are poorly understood by coastal oceanographers. The innershelf is generally too shallow for large oceanographic ships and too rough for smaller research vessels and as a consequence only limited studies have been carried out. Despite the paucity of scientific information, the innershelf is widely recognized to serve an important ecological function in the seasonal cycling of high productivity. At least three different models of circulation over the innershelf have been proposed. In the one-celled model, surface waters are transported offshore by the northwesterly winds (Huyer, 1976). This offshore transport is balanced by the upwelling of cold, high salinity water near the coast which then mixes with surface waters, is turned seaward, and transported offshore. Mooers (1976) proposed a two-celled model in which one cell develops in the nearshore and is separated from the offshore cell by a steep density gradient formed by the permanent pycnocline intersecting the sea surface. The nearshore cell is formed by cold, high salinity water upwelled immediately adjacent to the coast being moved offshore until its seaward progress is impeded by the surface density gradient. This dense upwelled water then sinks along isopycnals corresponding to the base of the permanent pycnocline. The offshore cell is formed by water upwelled from the top of the permanent pycnocline, which is then transported offshore at the surface. Wroblewski (1977) used the two celled circulation scheme to model phytoplankton biomass off the Oregon coast and found agreement between the model output and late summer field data.

To interpret spatial distribution patterns in zooplankton and chlorophyll an alternative two-celled model was proposed by Peterson et al. (1979). In this model the two cells lie on opposite sides of a divergence zone located approximately 10 km from shore. Northwesterly winds transport only a thin (≤ 5 m) surface layer offshore over both the nearshore and offshore cells. In the nearshore cell, the very shallow seaward flow of the surface water is balanced by shoreward flow at a depth of 10 m. Clockwise rotation of the nearshore cell typically occurs during the onset of upwelling events. Counterclockwise rotation of the offshore cell is similar to that proposed by Mooers (1976). In the offshore cell, water from the top of the permanent pycnocline is upwelled and transported offshore at the surface.

This investigation presents a series of physical and biotic studies carried out in the nearshore (0-5 km) and offshore (5- 80 km) regions of the southern Oregon coast. Samples were analyzed to asses phytoplankton distribution with a focus on the toxic diatom *Pseudo-nitzschia* spp. Results from the field samples and measurements were then interpreted within the context of the coastal circulation models and other earlier work. A conceptual model is put forth which is consistent with the data collected, and further areas of research are suggested.

Methods

Several sampling designs were employed under various meteorological and oceanographic conditions to investigate the physical, chemical, and biotic characteristics of the continental shelf waters near the mouth of Coos Bay, OR. The sampling designs included: A) a grid of stations located from the nearshore to the continental shelf break (May - June 1998); B) repeated sampling of a nearshore transect from the surf zone to 5 km offshore (Jul - Aug 1998); and C) repeated sampling of an offshore transect extending from 1 to 30 km offshore (1995-1997)(Figure 1).

McArthur Grid Sampling

A cross-shelf grid (Coos Bay Grid, CBG), which extended from the nearshore (4.8 km) to the continental shelf break, was sampled during the NOAA ship McArthur cruise AR-98-06 (May 28 - June 1, 1998). Gridlines were extended east to west at latitudes 43°20'N, 43°25'N, 43°30'N, 43°35'N, 43°40'N, 43°45'N, and 43°50'N (Figure 1). Sample stations were established along each at distances 4.8, 8, 16, 32, 48, 64, and 80 km offshore. Sampling was conducted 24 hours per day starting May 28 at the 4.8 km station on Gridline 1 (CBG1) and proceeded offshore to the 80 km station. Sampling continued along Gridline 2 (CBG2) from the 80 km station toward shore to the 4.8 km station. This onshore / offshore sampling pattern continued throughout the grid of stations (CBG 3-7).

Several physical and biological samples and measurements were taken at each station. The vertical structure and chlorophyll _a_ concentration of the water column was determined using a Seabird 911 Conductivity-Temperature-Depth (CTD) meter with an attached Wetstar Wetlabs flourometer. The CTD was lowered until 5 meters above bottom or to a maximum of 300 meters. The locations of the pycnocline and chlorophyll _a_ maximum were determined during the CTD downcast. Whole water samples were collected from a rosette of 2.5 liter Niskin bottles deployed with the CTD. The Niskin bottles were triggered on the CTD upcast at 4 depths: a) 100

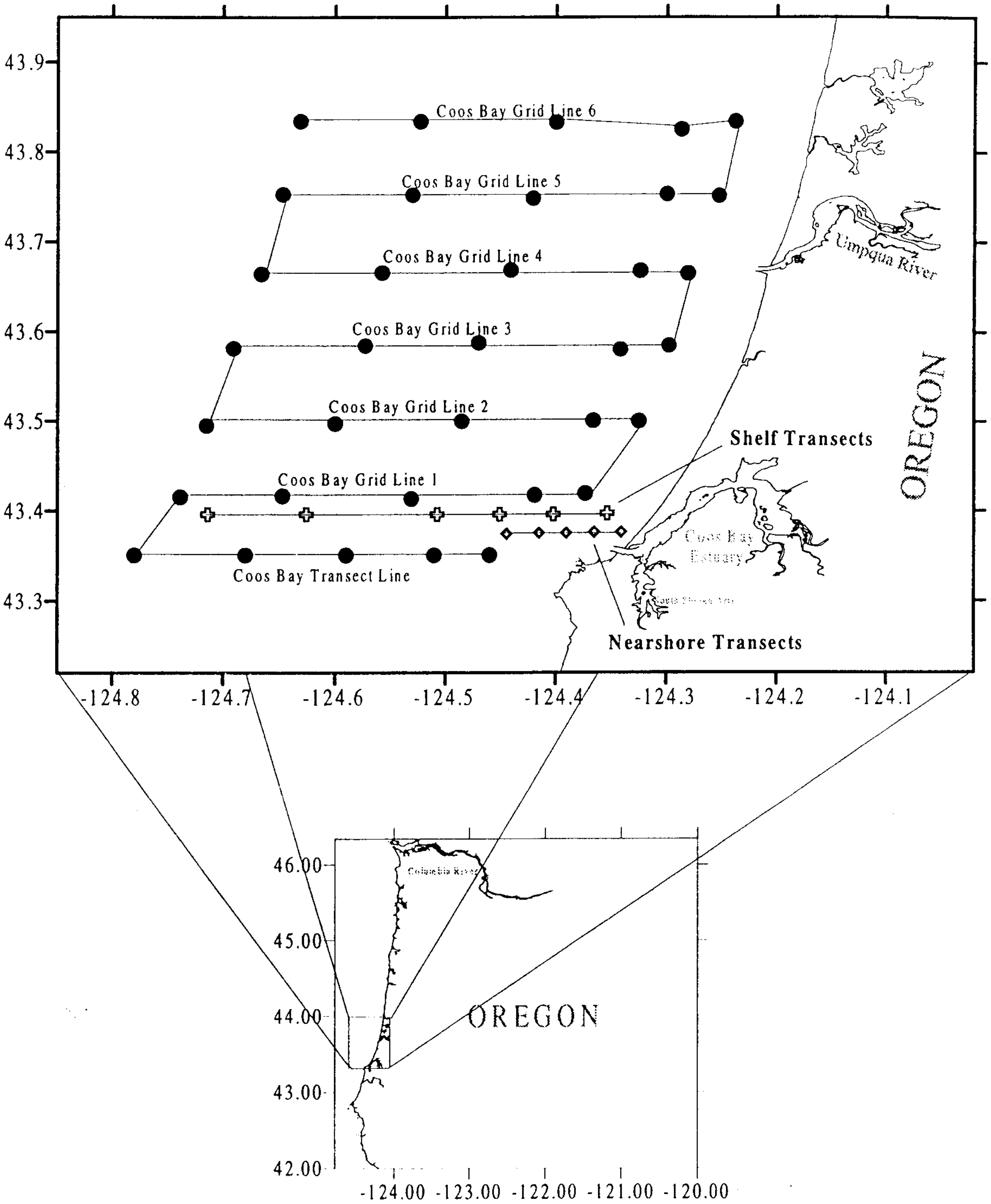


Figure 1: Map of Coos Bay Sampling Grid (CBG), Nearshore and Shelf Transects

meters, b) at the pycnocline, c) at the chlorophyll a maximum, and d) at 3 meters below surface. Subsamples of seawater (250 ml) were taken from the Niskin bottles for phytoplankton enumeration and nutrient analysis. The phytoplankton subsamples were preserved with acidic Lugol's solution and the nutrient subsamples were immediately frozen at -20°C.

Upon return to the laboratory 20 ml subsamples of the preserved phytoplankton were filtered through a 0.45 μM Millipore filter and stained with Fast Green as described in Parsons (1985). The stained samples were counted at 100x using a Leitz compound microscope. Phytoplankton were identified to genus and to species when possible.

Nutrient samples were thawed, filtered and acidified before being sent to Lamont-Dogherty Earth Observatory for analysis with a QuikChem 8000 autoanalyzer (Lachat Instruments). Samples were analyzed for Nitrate, Phosphate, and Silicate.

Nearshore and Shelf Transect Sampling

A transect located north of the mouth of Coos Bay at 43°.21' N and extending from 1 to 30 km offshore was sampled during the fall of 1995 - 1997 (Figure 1) from the fishing vessel Betty Kay. Sampling was carried out under various meteorological and oceanographic conditions to determine the physical characteristics of the water column and the associated distribution of phytoplankton. The first station was located ~ 2 km offshore and subsequent stations were located at 5, 10, 15, 20, and 30 km offshore. A number of additional nearshore transects were sampled during the fall of 1997 using the 5 m R/V Bayrunner. The nearshore transects were also located just north of the mouth of Coos Bay and consisted of five stations. The first station was ~

500 m offshore, just outside the surf zone. The subsequent stations were spaced ~ 1 km apart with the transect ending at ~ 5 km offshore.

At each station a CTD cast was made to determine temperature, salinity, and density. A flourometer attached to the CTD was used to measure chlorophyll a. Water samples were collected from the surface and at depth with a 2.5 liter Niskin bottle. When conditions allowed the CTD cast was monitored in real-time with a laptop computer to ascertain the depth of the pycnocline and chlorophyll a maximum, if they existed. Water samples were collected with the Niskin bottles from 3 depths: a) surface, b) in the chlorophyll a maximum, and c) below the chlorophyll a maximum . Subsamples (250 ml), for phytoplankton and nutrient analysis, were retrieved from the Niskin bottles and preserved and analyzed as described above.

Results

McArthur Grid (Coos Bay Grid)

Winds

Winds varied greatly in speed and direction during the weeks preceding McArthur cruise AR-98-06 (Figure 2). The predominant winds for May 15 - 20 were from the north with speeds between 0 - 8 m/s. On May 21 - 26, the winds shifted and came from the south, although they were highly variable, with speeds again between 0 - 8 m/s. On May 27 - 28, the first two days of the cruise, winds were once again from the north and still variable in speed , 0 - 4 m/s. On May 29 and part of May 30 the winds shifted again, to blow consistently from the south at 0 - 5 m/s. The final reversal took place at noon on the May 30 with steady north winds at 2.5 - 8 m/s, which continued for the remainder of the cruise.

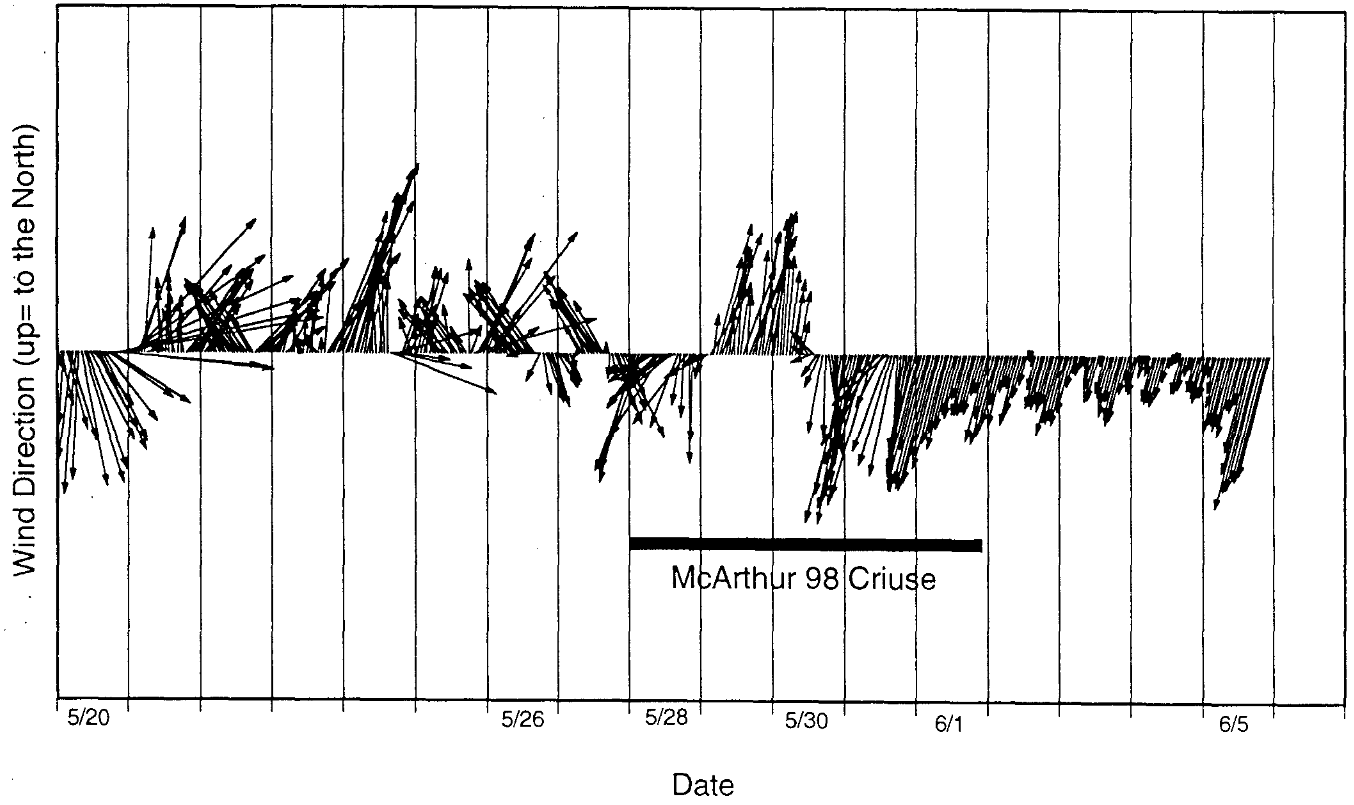


Figure 2: Wind vector plot during McArthur Cruise AR-98-06 May 20 - June 5, 1998

Permanent and Seasonal Pycnoclines

The permanent pycnocline (25.5 - 26.0 sigma-t) as defined by Mooers et al. (1976), was sloped upward toward the shore, but did not intersect the sea surface at any point in the grid (Figure 3). At the stations 32 km offshore, the depth of the pycnocline was ~ 100 m and at the 5 km stations it was found at ~ 45 m. The region just north of the Cape Arago headlands, near the mouth of Coos Bay, had the shallowest pycnocline depth (~ 40 m). Generally the depth of the permanent pycnocline followed the bathymetry of the region as recorded by the ship. The slight slope of the permanent pycnocline and its lack of intersection with the sea surface suggest that the variable winds had not generated active upwelling.

A seasonal pycnocline, formed by waters with a density of 23.5 - 24.5 sigma -t, was observed throughout the grid (Figure 4-9). This pycnocline was consistently located at a depth of ~ 10 - 15 m, was virtually horizontal, and at no point intersected the sea surface. The range of densities encountered were 20.0 - 26.5 sigma -t. With the exception of three nearshore stations, the density in the surface waters was ~ 23.0 sigma -t increasing to 26.5 in the deeper waters sampled at the offshore stations.

Salinities encountered over the entire grid ranged from 27.0 - 33.5 psu (Figures 4-9). A halocline corresponding to the seasonal pycnocline consisted of water with salinities of 31 - 32 psu. The halocline was virtually horizontal and occurred at a depth of ~ 10 - 15 m. Similarly, a horizontal thermocline was located at 10 - 15 m with temperatures between 11 - 12 °C. Temperatures ranged from 8 - 13.5 °C throughout the stations sampled (Figures 4-9). Offshore surface waters were slightly warmer than the nearshore surface waters.

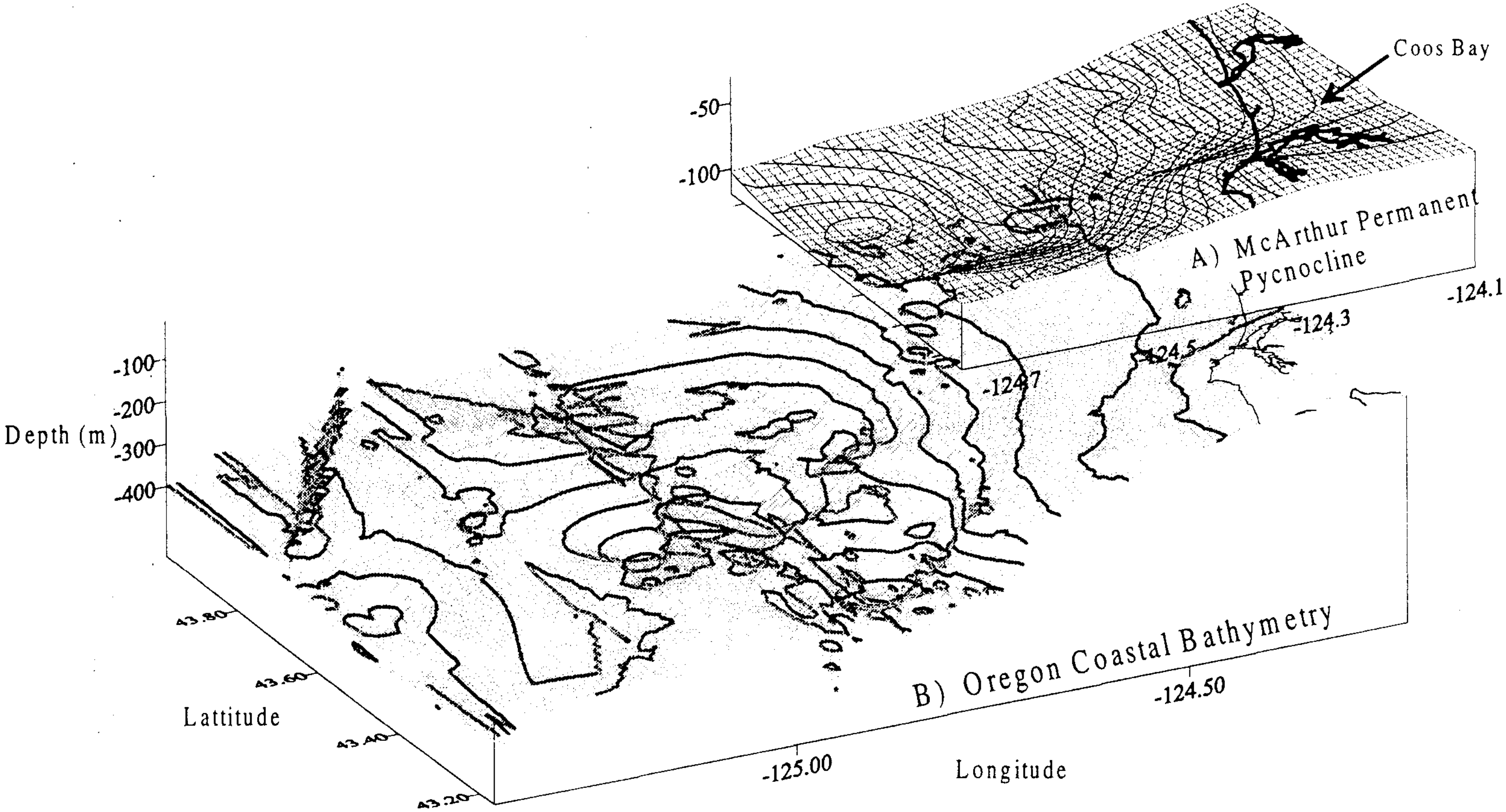


Figure 3: Contour plots of A) permanent pycnocline (25.5-26.0 sigma-t) and B) coastal bathymetry for Coos Bay Grid May 28 – June 1, 1998

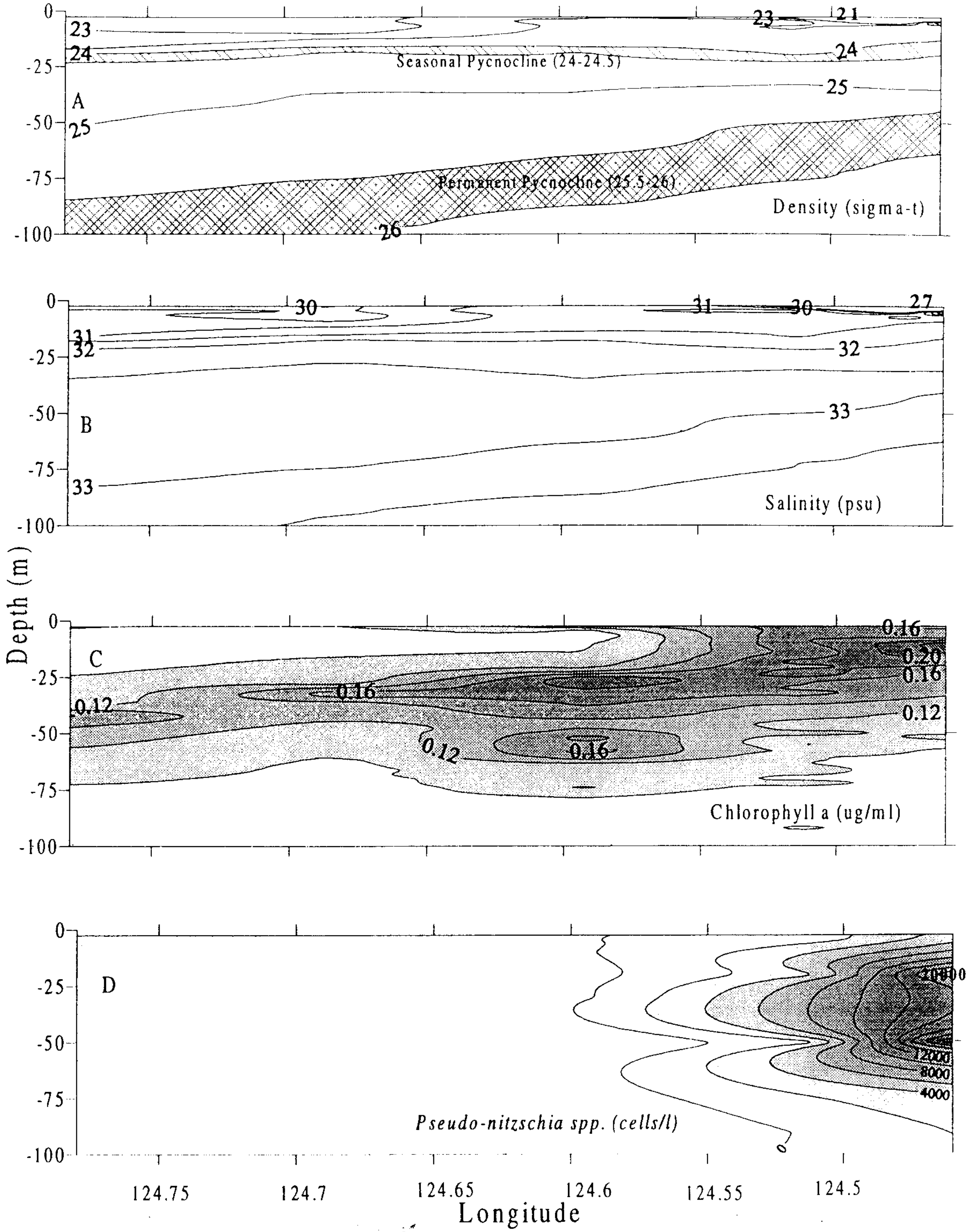


Figure 4: Contour plots for the Coos Bay Transect Line A) Density, B) Salinity, C) Chlorophyll a and D) *Pseudo-nitzschia* spp.

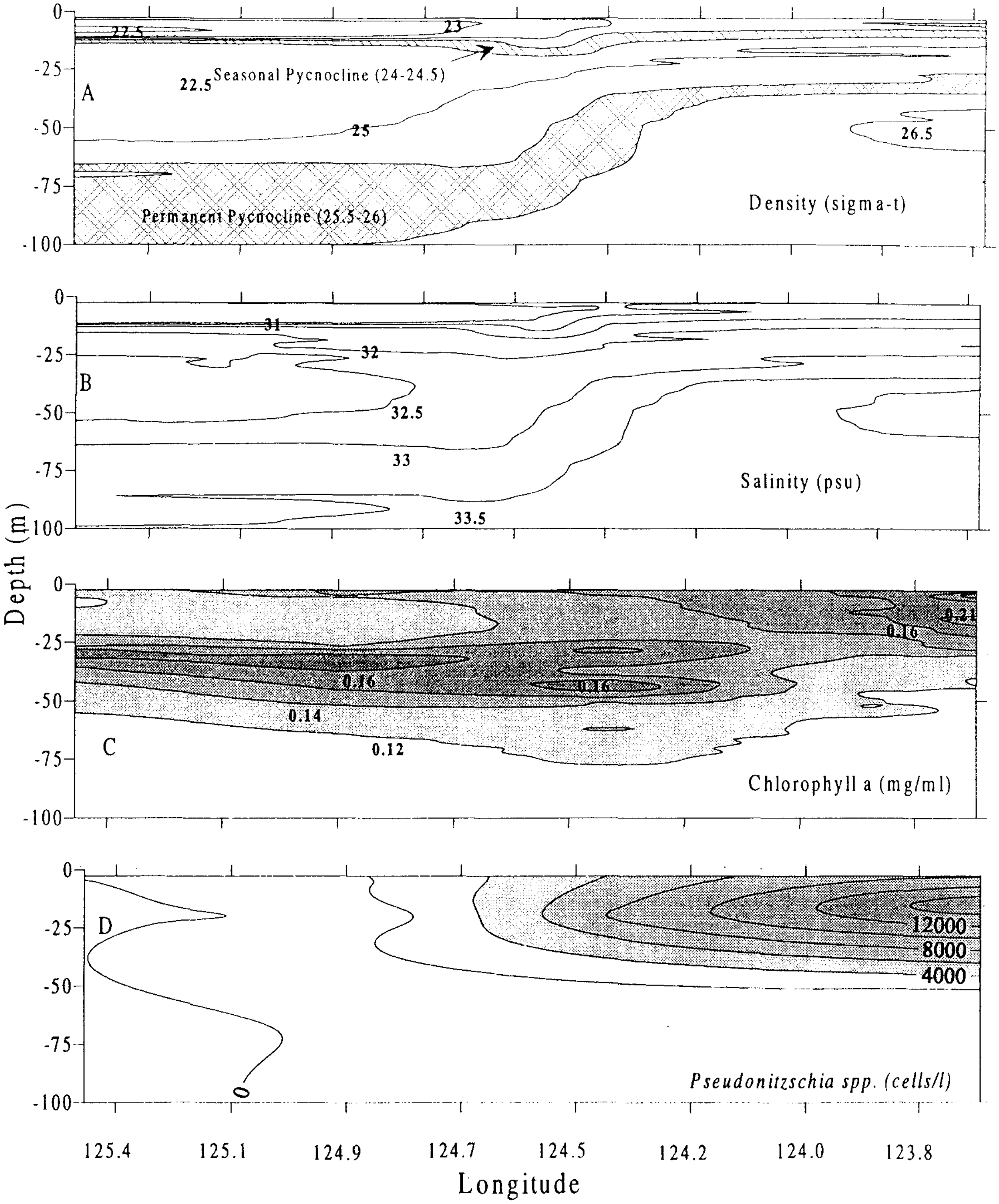


Figure 5: Contour plots for the Coos Bay Grid Line 1 (CBG1) A) Density, B) Salinity, C) Chlorophyll a and D) *Pseudo-nitzschia* spp.

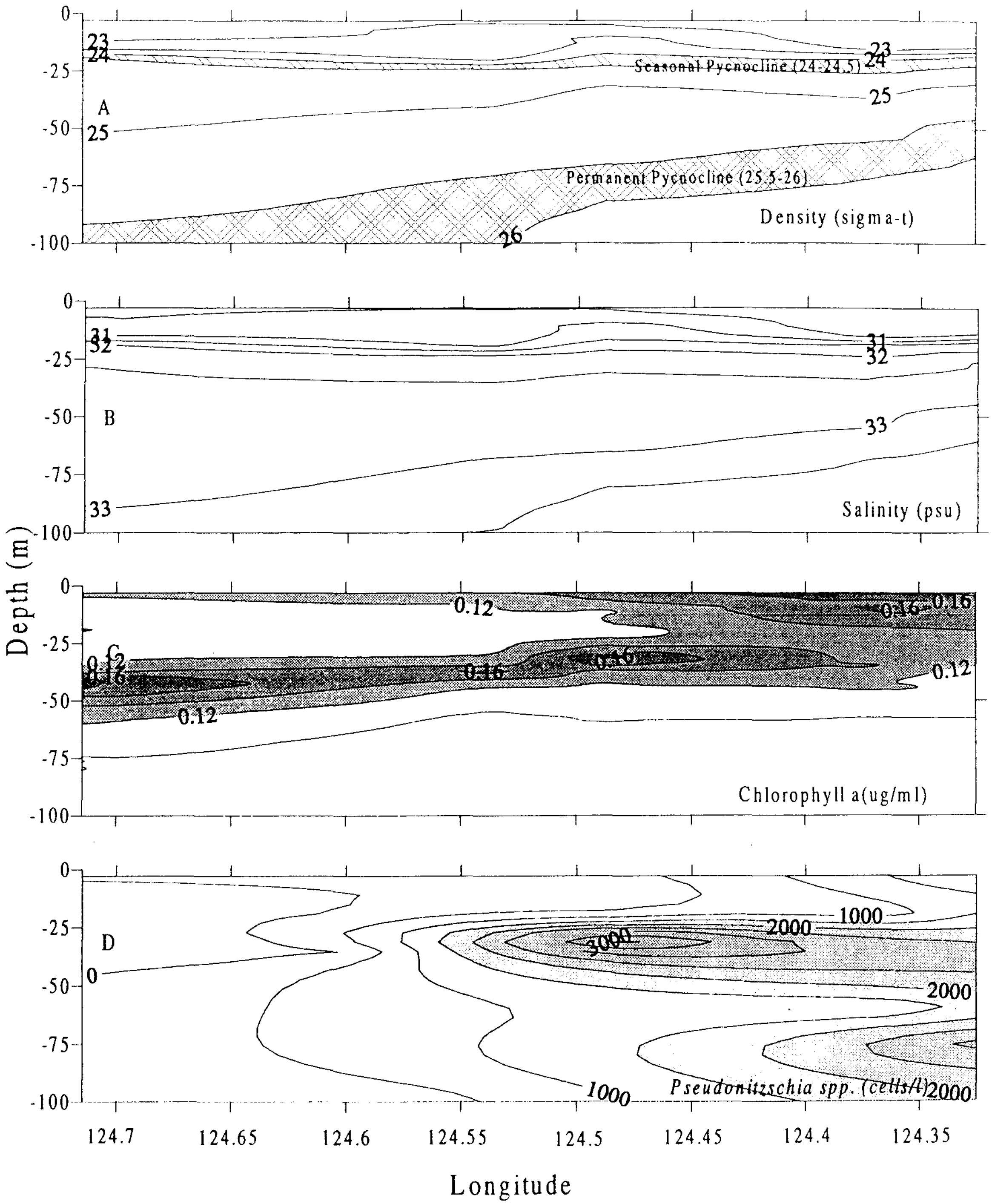


Figure 6: Contour plots for the Coos Bay Grid Line 2 (CBG2) A) Density, B) Salinity, C) Chlorophyll a and D) *Pseudo-nitzschia* spp.

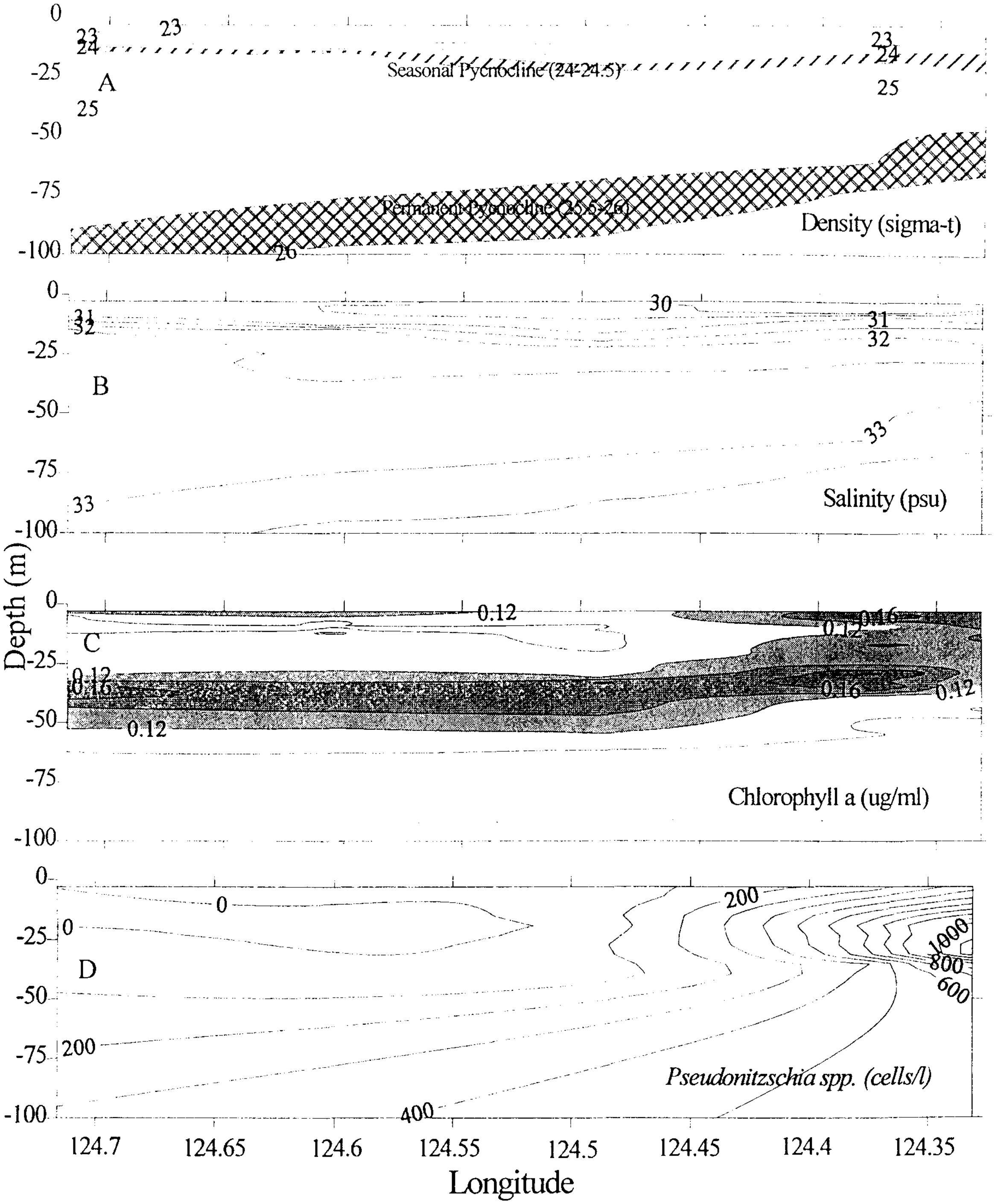


Figure 7: Contour plots for the Coos Bay Grid Line 4 (CBG4) A) Density, B) Salinity, C) Chlorophyll a and D) *Pseudo-nitzschia* spp.

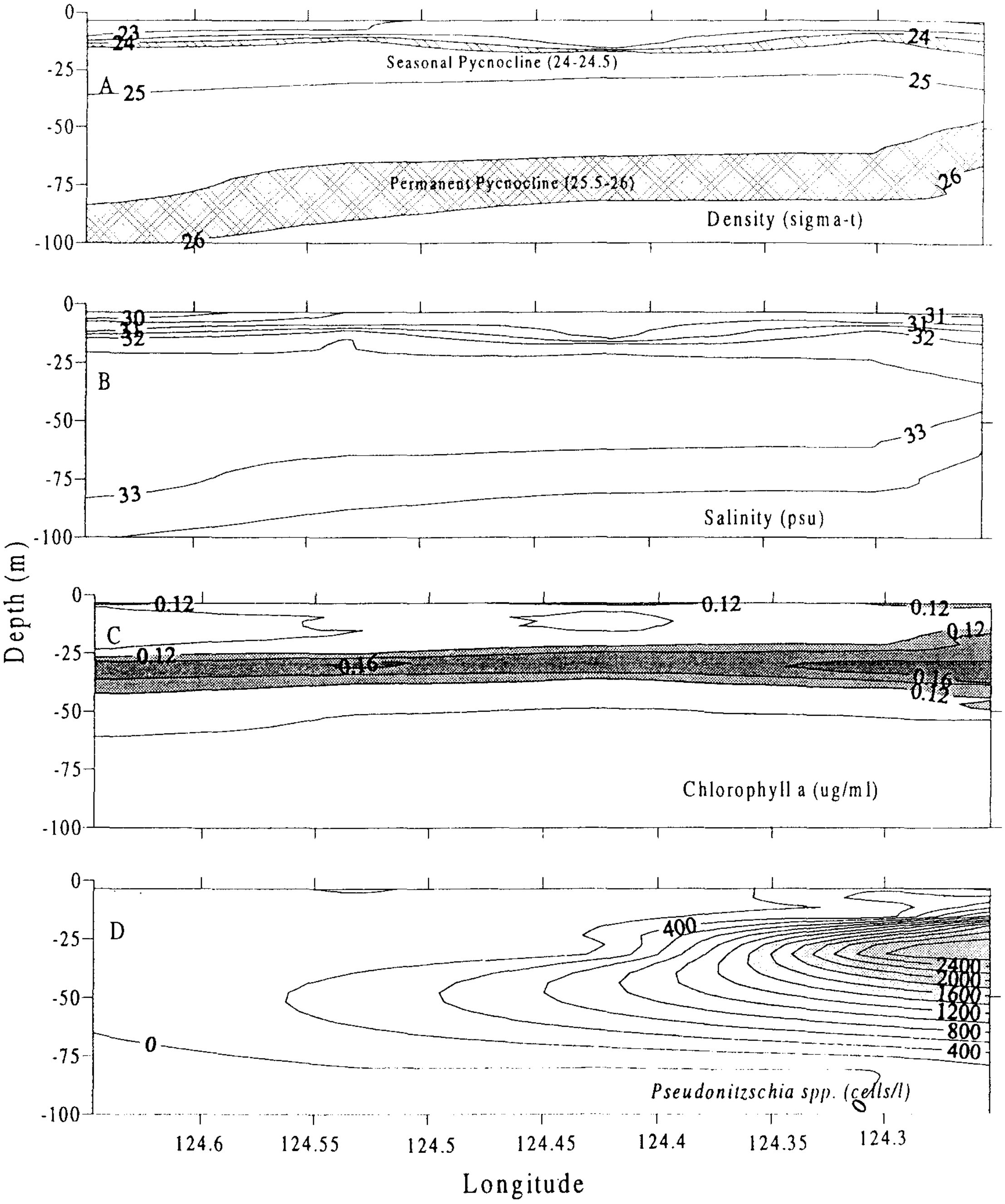


Figure 8: Contour plots for the Coos Bay Grid Line 5 (CBG5) A) Density, B) Salinity, C) Chlorophyll a and D) *Pseudo-nitzschia* spp.

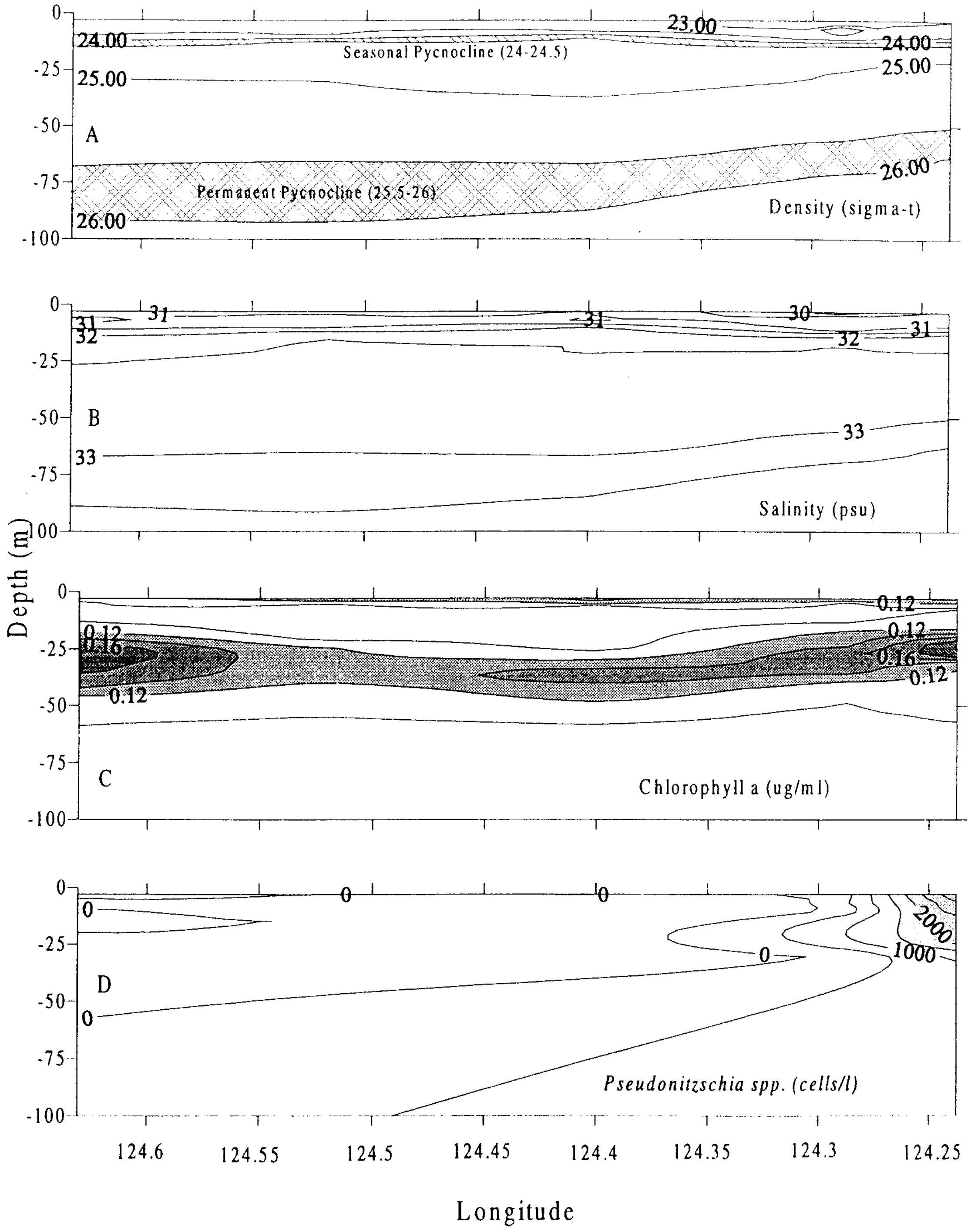


Figure 9: Contour plots for the Coos Bay Grid Line 6 (CBG6) A) Density, B) Salinity, C) Chlorophyll a and D) *Pseudo-nitzschia* spp.

A lens (~ 5 m deep) of low density water (20 sigma -t) was located at the nearshore stations in front of both Coos Bay and the Umpqua River and extended 5 - 10 km offshore (Figures 4 and 7). The reduced density found at these stations was due to the lower salinity water (27 - 29 psu) found there. The low salinity water was riverine input from Coos Bay and the Umpqua River. The region of reduced density around the mouth of Coos Bay encompassed two nearshore stations (CBL 1.1 and CBG1.1) while the region at the mouth of the Umpqua River influenced one nearshore station (CBG 4.1).

Nutrients

Water samples collected at various depths along grid lines CBG 2, 4, 5, and 6 were analyzed for concentrations of nitrate, phosphate, and silicate (Table 1a-d). Nitrate concentrations ranged from 0.006 - 23.6 μM while phosphate concentrations ranged from 0.05 - 1.57 μM. The maximum concentrations were found in the deepest samples taken from below the permanent pycnocline (100 m). In shallower samples, taken from above the pycnocline, both nitrate and phosphate concentrations were greatly reduced with the maximum, albeit low, values found at the nearshore stations on CBG 6. Silicate concentrations ranged from 0.54 - 40.29 μM again with the highest values found in deep samples (75 m). Interestingly, relatively high silicate concentrations were found in the surface samples from the nearshore stations on CBG 4, located at the mouth of the Umpqua River (Table 1b). These concentrations decreased with depth and provide correlative evidence for an association with the low salinity surface waters observed at these stations. No nutrient samples were taken from the waters near the mouth of Coos Bay.

Table 1: Nutrient concentrations for Coos Bay Grid: A) CBG 2, B) CBG 4, C) CBG 5, and D) CBG 6 for phosphate, silicate, and nitrate.

A

Station	Depth (m)	Phosphate (μM)	Silicate (μM)	Nitrate (μM)
2.1	3	0.136	11.58	0.835
2.1	20	0.047	9.39	0.401
2.1	50	0.804	22.5	15.05
2.1	75	1.322	40.29	23.62
2.2	3	0.061	6.64	0.264
2.2	20	0.087	1.44	0.399
2.2	60	1.047	22.394	16.49
2.3	3	0.32	6.366	0.268
2.3	20	0.318	5.519	0.026
2.3	30	0.529	2.106	0.17
2.4	3	0.193	3.26	0.303
2.4	20	0.308	3.11	0.613
2.4	35	1.8	36.55	20.38
2.4	100	1.57	27.186	20.343
2.5	3	0.198	3.99	0.51
2.5	45	0.55	2.88	1.83
2.5	100	0.916	13.4	9.224

B

Station	Depth (m)	Phosphate (μM)	Silicate (μM)	Nitrate (μM)
4.1	3	0.127	20.661	1.036
4.1	20	0.169	19.766	0.573
4.1	30	0.305	6.47	1.028
4.2	3	0.269	14.047	0.768
4.2	25	0.235	11.71	0.5
4.2	35	0.319	0.815	1.694
4.3	3	0.078	4.379	0.258
4.3	20	0.234	1.7	0.119
4.3	40	0.313	2.966	1.937
4.4	3	0.194	3.47	0.176
4.4	15	0.44	1.99	0.277
4.4	40	0.525	2.97	0.54
4.5	3	2.9	3.2	0.83
4.5	15	0.191	2.77	0.146
4.5	35	0.239	3.925	0.076

Table 1: Cont.

C

Station	Depth (m)	Phosphate (µM)	Silicate (µM)	Nitrate (µM)
5.1	3	0.075	3.87	0.487
5.1	20	0.369	0.543	0.22
5.1	30	0.504	2.426	2.856
5.2	3	0.545	2.116	1.49
5.2	15	0.104	1.823	0.565
5.2	30	0.048	4.557	0.722
5.3	3	0.21	2.383	0.56
5.3	15	0.065	2.78	0.288
5.3	30	0.127	3.51	0.939
5.4	3	0.422	1.815	0.525
5.4	10	0.152	2.08	0.091
5.4	30	0.152	2.857	0.233
5.5	3	0.175	3.084	0.006
5.5	15	0.159	3.155	0.264
5.5	30	0.274	1.134	0.166

D

Station	Depth (m)	Phosphate (µM)	Silicate (µM)	Nitrate (µM)
6.1	3	0.626	2.658	3.317
6.1	10	0.675	2.99	3.447
6.1	25	0.672	2.795	3.349
6.2	3	0.272	4.695	0.141
6.2	10	0.188	3.738	0.236
6.2	30	0.582	4.064	2.82
6.3	3	0.27	2.27	0.007
6.4	3	0.186	2.133	0.143
6.4	15	0.27	2.27	0.007
6.4	30	0.44	4.2	3.29
6.5	3	0.411	2.27	0.989
6.5	15	0.346	1.71	0.124
6.5	20	0.224	2.27	0.211

Chlorophyll a

Chlorophyll a concentrations varied with a range of 0.0 - 2.2 µg/l (Figures 4-9). Maximum concentrations were found in the surface layers (0 - 25m) of the nearshore stations off the mouth of Coos Bay (Figures 4 and 5) . The chlorophyll a distribution followed a similar pattern in the first four transects from the mouth of Coos Bay (CBL) to the transect in front of the Umpqua River (CBG 4) (Figures 4-7). In these transects, a nearshore maximum was located in the surface layers extending to a depth of ~ 25 m. In contrast, the two northern most transects (CBG 5 and 6, Figures 8 and 9), had two zones of higher chlorophyll a concentration, one in the surface waters at 0 - 5 m and the other at a depth of 20 - 30 m.

Further from shore and in all transects, the chlorophyll a maximum was located between 20 - 30 m, just beneath the seasonal pycnocline (Figures 4-9). At depths greater than 40 m chlorophyll a concentrations dropped off markedly. At the stations farthest offshore, an increased concentration of chlorophyll a was found at depths between 30 - 40 m, in all of the transects.

Pseudo-nitzschia spp.

Highest concentrations of *Pseudo-nitzschia* spp. were found in the nearshore samples of each transect (Figures 10), with a maximum of $2.2\text{x}10^4$ cells/l in the samples taken near the mouth of Coos Bay. None of the samples from the offshore stations contained a high concentration of *Pseudo-nitzschia* spp. at any depth. In the nearshore samples, the depth at which the highest cell concentrations were found varied between transects.

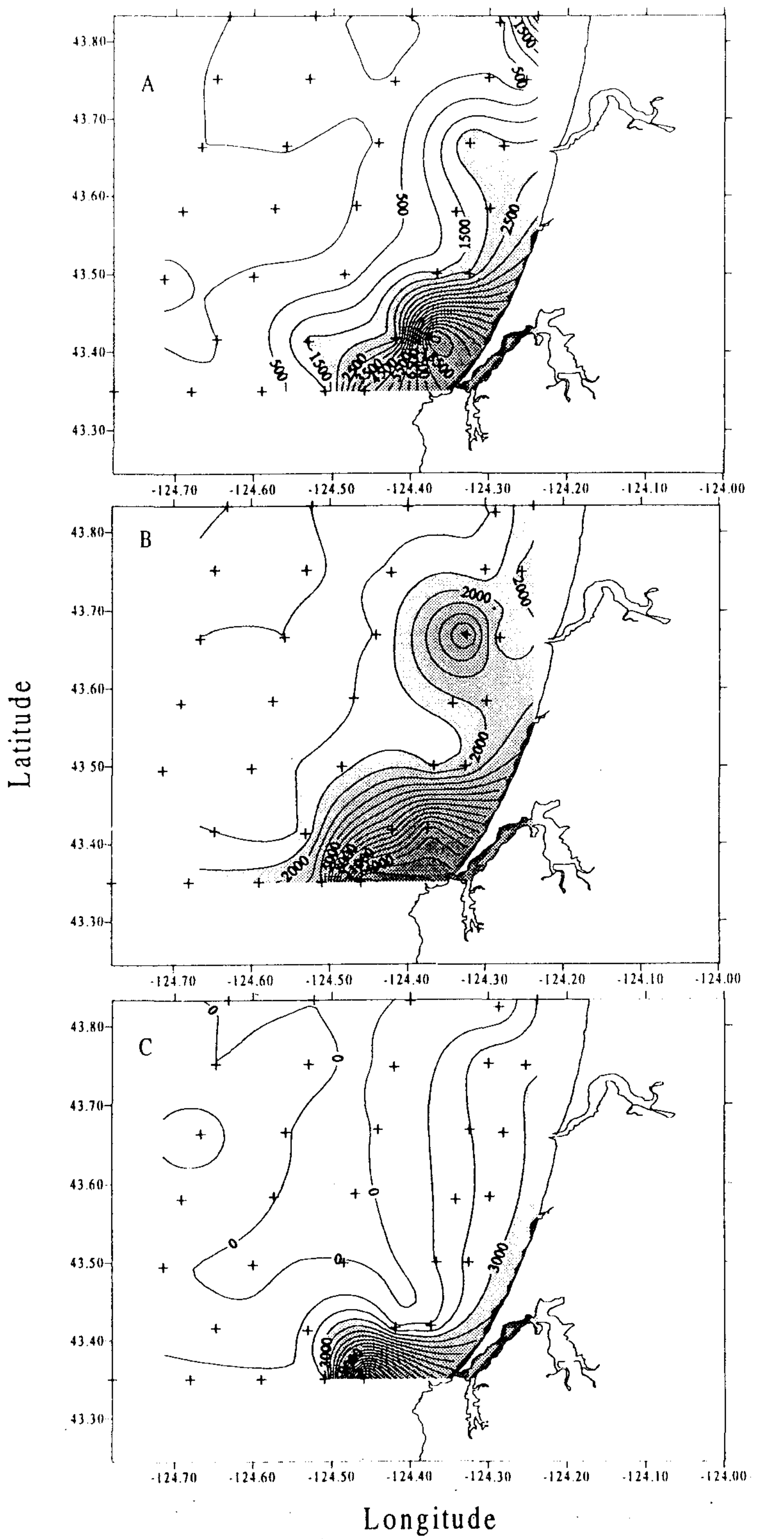


Figure 10: *Pseudo-nitzschia* spp. concentrations (cells/l) at three depths: A) surface, B) chlorophyll a maxima, and C) below chlorophyll a maxima for Coos Bay Grid May 28 – June 1, 1998

In the nearshore station on the Coos Bay Line, in front of the mouth of Coos Bay, the surface waters high concentrations ($2.2\text{x}10^4$ cell/l) of *Pseudo-nitzschia* spp. extending to 50 m (Figure 4). Samples from below 50 m revealed lower ($4.2\text{x}10^3$), but still high, cells concentrations. During enumeration of the samples it was noted that many of the cells (~ 30%) from the deeper samples were singlets and appeared to be in poor shape often without intact cell walls. At stations further offshore (8 km) along the CBL, the highest abundance of cells ($3.8\text{x}10^3$ cells/l) was found at 20 m depth, with fewer cells in the surface waters and at depth. At stations past 16 km, along the CBL, no *Pseudo-nitzschia* spp. cells were found in samples from any depth.

Along Coos Bay Grid Line 1 the highest *Pseudo-nitzschia* spp. concentrations ($1.0\text{x}10^4$ - $1.5\text{x}10^4$ cells/l) were in the upper 20 m at the nearshore station (Figure 5). Moving offshore, cell concentrations decreased with the maximum value ($8.5\text{x}10^3$ cells/l) found in the 20 m sample at the 8 km station. Again stations further offshore had very few *Pseudo-nitzschia* spp. cells.

Coos Bay Grid line 2 had lower concentrations than the more southern transects but again the highest concentration of cells were found at the nearshore station (Figure 6). Cell concentrations ranged between $1.5\text{x}10^3$ - $2.3\text{x}10^3$ cells/l in the upper water column (3 - 50 m). The highest concentration of cells ($3.1\text{x}10^3$ cells/l) was found in the bottom sample at 75 m. The cells from these samples were again in poor condition and often without chloroplasts. Cell concentrations decreased offshore with one exception; in the 30 m sample at the 16 km station concentrations reached $4.3\text{x}10^3$ cells/l.

In the samples from Coos Bay Grid 4 and Coos Bay Grid 5 the highest cell concentrations were in the nearshore samples, below the seasonal pycnocline, from depths of 20-30 m (Figures 7 and 8). Concentrations ranged from $1.2\text{x}110^3$ - $1.4\text{x}10^3$

cells/l on CBG4 and 2.3×10^3 - 2.8×10^3 cells/l on CBG5. Cell concentrations rapidly decreased at stations further offshore. Coos Bay Grid 6 had high cell concentrations in the surface waters and these high concentrations extended to a depth of 25 m with values ranging between 2.0×10^3 - 3.5×10^3 cells/l (Figure 9).

Nearshore and Shelf Transects

The wind conditions preceding each of the sampling dates varied between upwelling favorable winds and relaxation events. The differences in wind conditions were apparent in the physical structure of the water column and the distributions of phytoplankton. Results from the shelf and nearshore transects were divided, according to the preceding wind conditions and the physical characteristics of the water column, into three categories: 1) early upwelling, 2) early relaxation, and 3) relaxation.

Category 1 - Early Upwelling

Shelf Transect #1 October 30, 1995

The wind conditions in the week preceding the sampling (Oct 18 - 25) were characterized by variable winds, followed by southwesterly winds which began on Oct 26 and blew at 2 - 7 m/s. During Oct 27 - 30 winds were northwesterly at 2 - 5 m/s and, by the day of the cruise, had weakened to 1 - 2.5 m/s (Figure 11a).

The physical characteristics of the water column were exemplified by the upward sloping isopleths of temperature, salinity, and density (Figure 11b). The density of the nearshore water was 24.4 - 25.4 sigma -t and was derived from above the permanent pycnocline (25.5 - 26 sigma -t) (Mooers, 1976). These waters were the same density as the seasonal pycnocline which was located at 25 - 30 m depth at

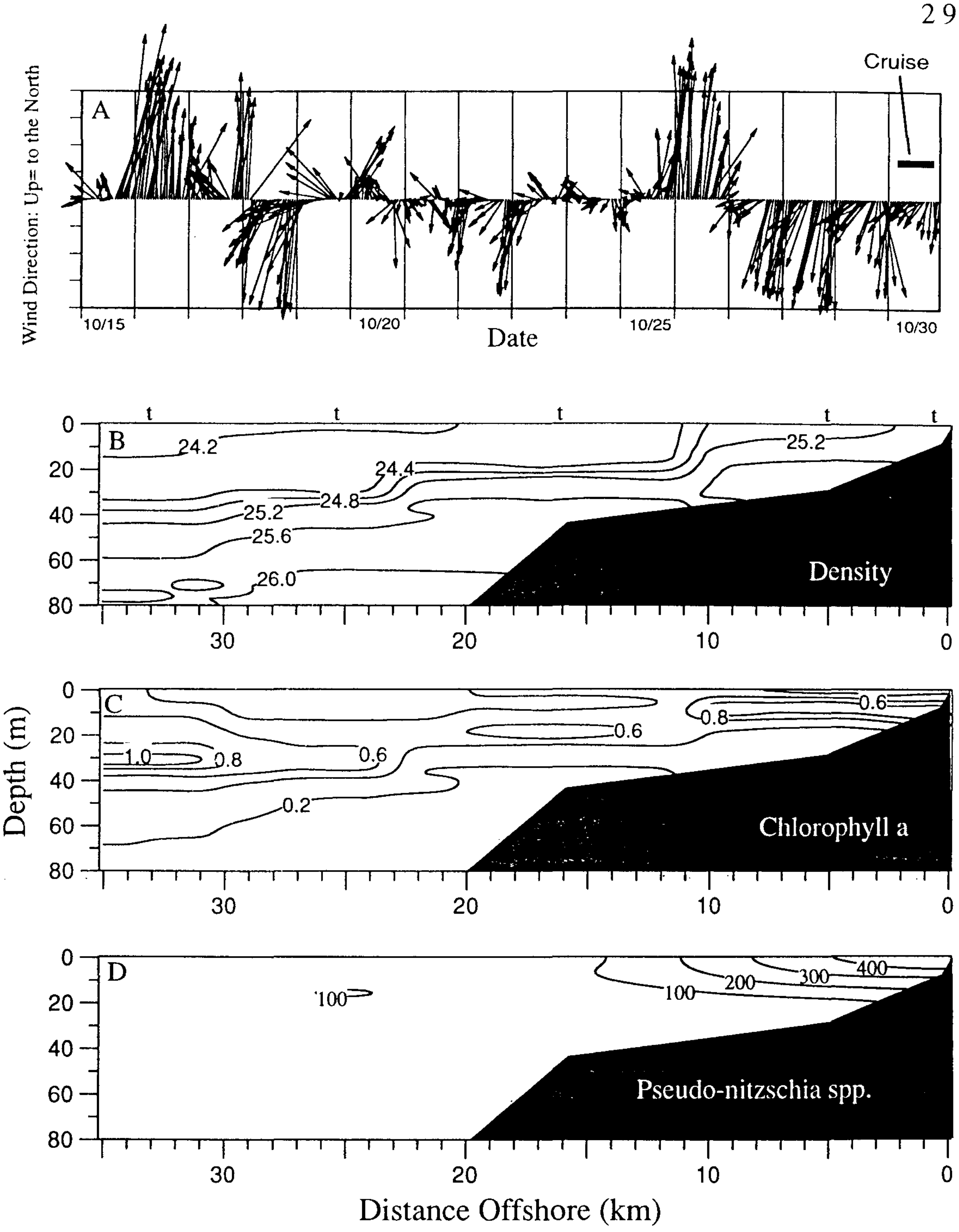


Figure 11: Shelf Transect #1 Oct. 30, 1995; A) Wind vector plot (m/s), B) Density (sigma-t), C) Chlorophyll a (mg/l), and D) Pseudo-nitzschia spp. (cells/l) contour plots

stations further offshore. Chlorophyll a concentrations were highest nearshore and at a depth of ~ 10 m. Stations between 10 and 20 km offhsore had low concentrations of chlorophyll a at all depths (Figure 11c). At the 30 km station, an elevated concentration of chlorophyll a was located on the seasonal pycnocline at ~ 30 m depth. *Pseudo-nitzschia* spp. distribution followed the same pattern as the overall chlorophyll a distribution, with two areas of higher concentrations. The highest concentration of *Pseudo-nitzschia* spp. was located in the surface waters at the stations closest to shore. A second area of higher *Pseudo-nitzschia* spp. concentration was located between 20 -30 km offshore, at a depth of ~ 30 m (Figure 11d).

Category 2 - Early Relaxation

This category included the following transects:

1) Shelf Transect #2 October 10, 1996
2) Shelf Transect #3 July 31, 1997
3) Shelf Transect #4 October 27, 1997
4) Nearshore Transect #1 July 17, 1997
5) Nearshore Transect #2 July 29, 1997

The winds preceding each of these transects were similar in nature. Prior to each date, upwelling (e.g. NW) winds decreased in strength followed by a reversal in direction on or shortly before the sampling date. In each case the northwesterly upwelling generating winds ranged in strength from 2 - 5 m/s and the southwesterly, relaxation or downwelling generating winds, were at about 1 - 3 m/s (Figures 12a-16a).

The shelf transects were characterized by a slight upward tilt of the isopleths of temperature, salinity, and density toward shore, while the isopleths along the

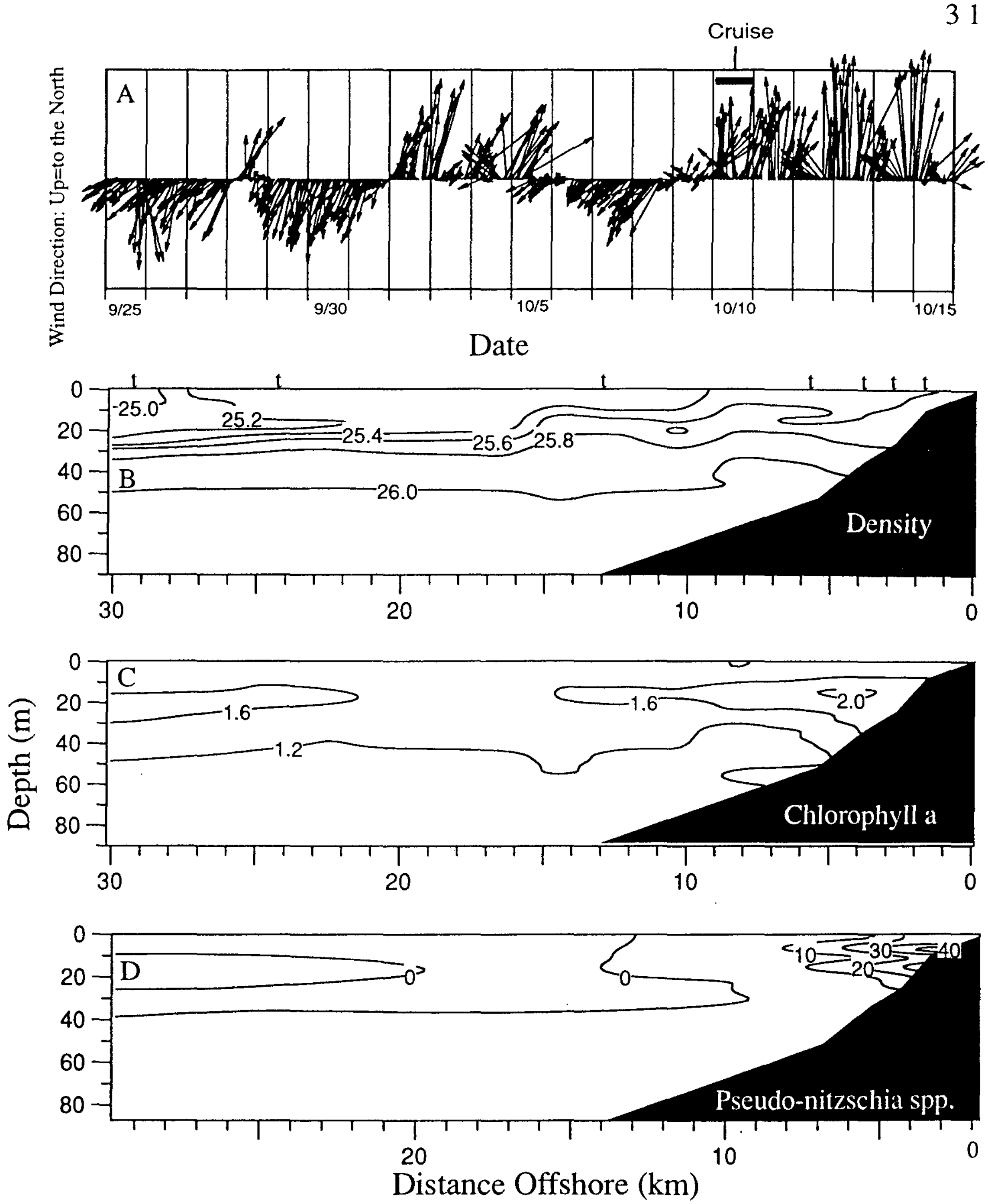


Figure 12: Shelf Transect #2 Oct. 10, 1996. A) Wind vector plot (m/s), B) Density (sigma-t), C) Chlorophyll a (mg/l), and D) Pseudo-nitzschia spp. (cells /ml) contour plots.

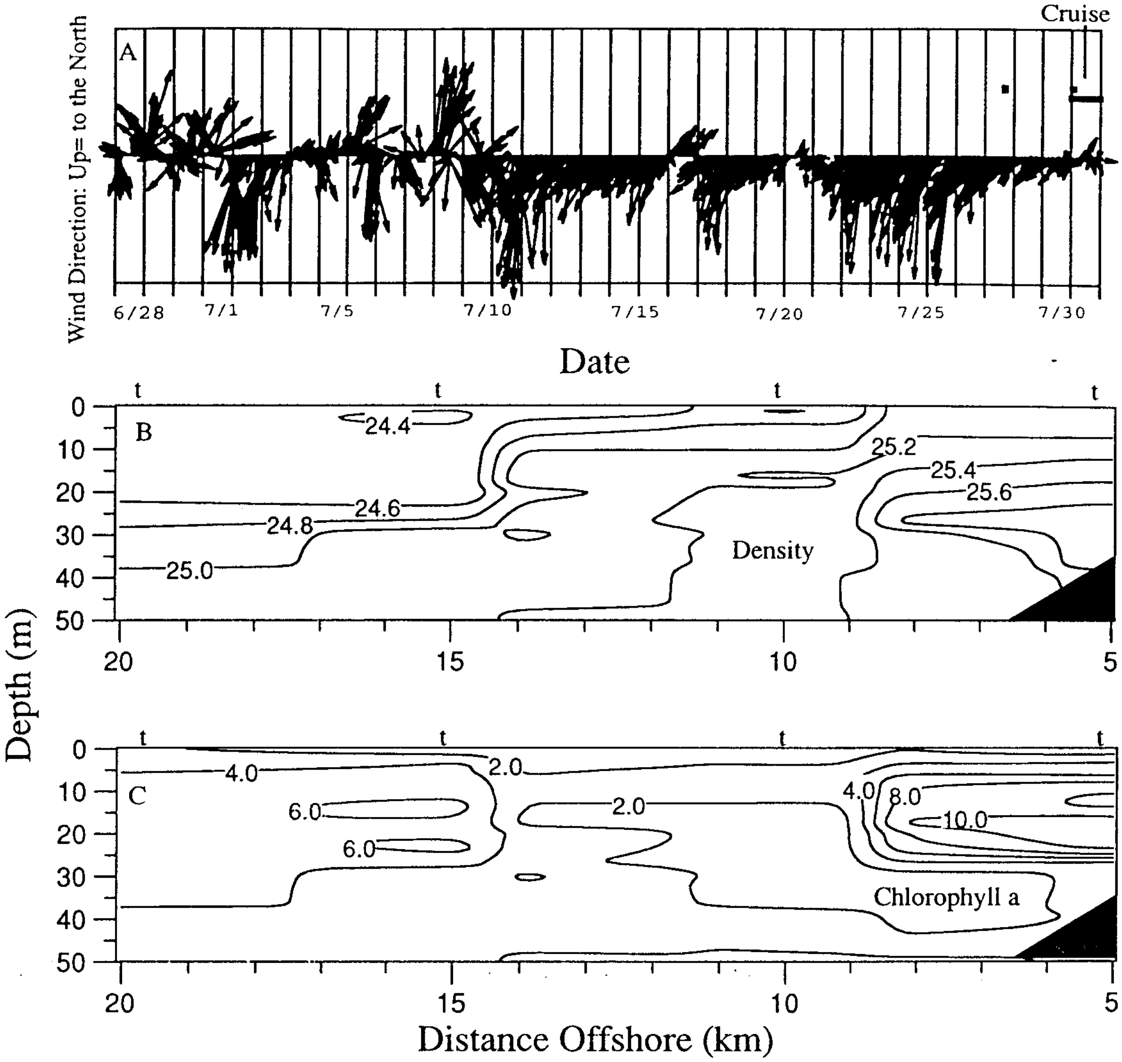


Figure 13: Shelf Transect #3 July 31, 1997; A) Wind vector plot (m/s), B) Density (sigma-t), C) Chlorophyll a (mg/l) contour plots

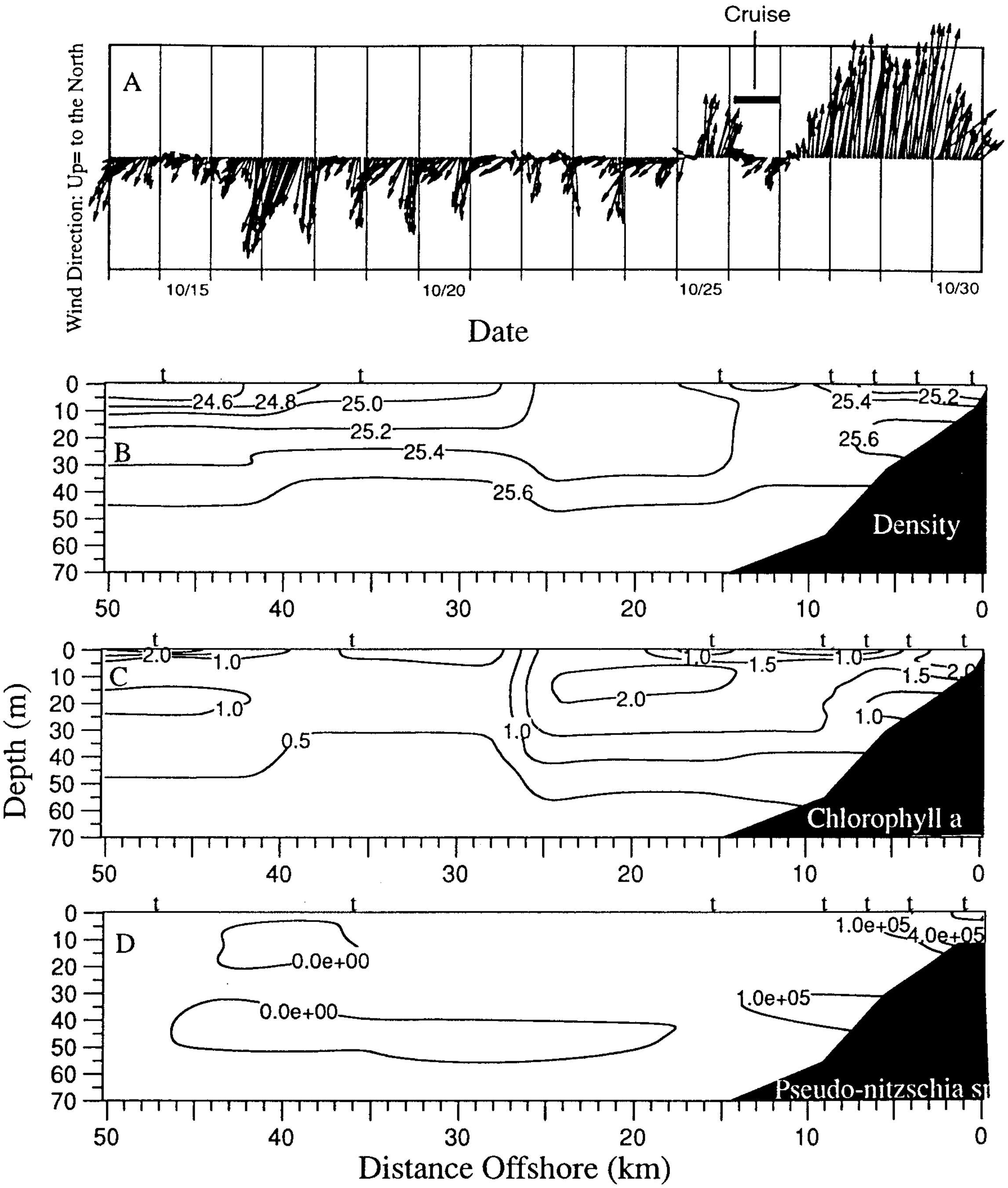


Figure 14: Shelf Transect #4 Oct. 27, 1997; A) Wind vector plot (m/s), B) Density (sigma-t), C) Chlorophyll a (mg/l), and D) Pseudo-nitzschia spp. (cells/l) contour plots

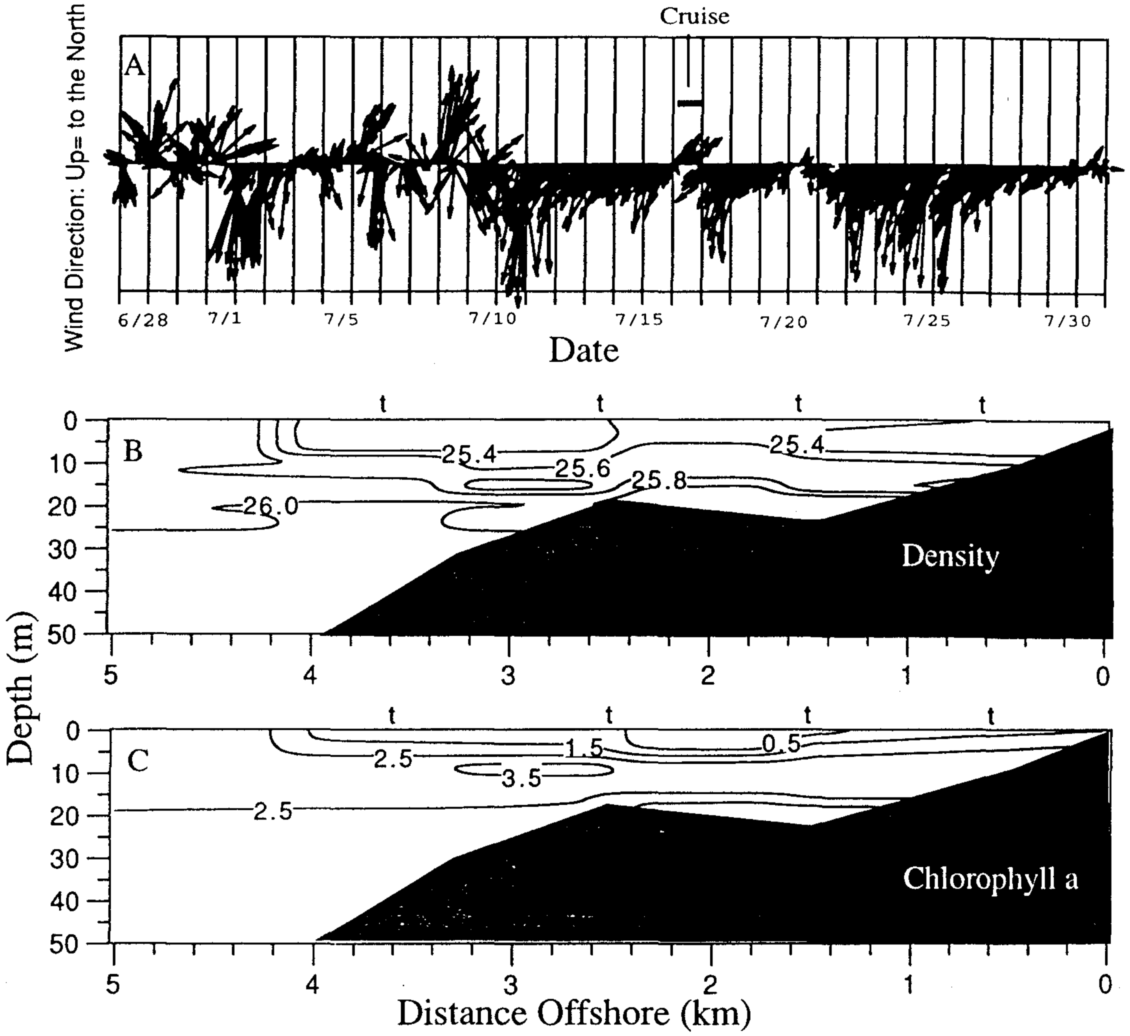


Figure 15: Nearshore Transect #1 July 17, 1997; A) Wind vector plot (m/s), B) Density (sigma-t), and C) Chlorophyll a (mg/l) contour plots

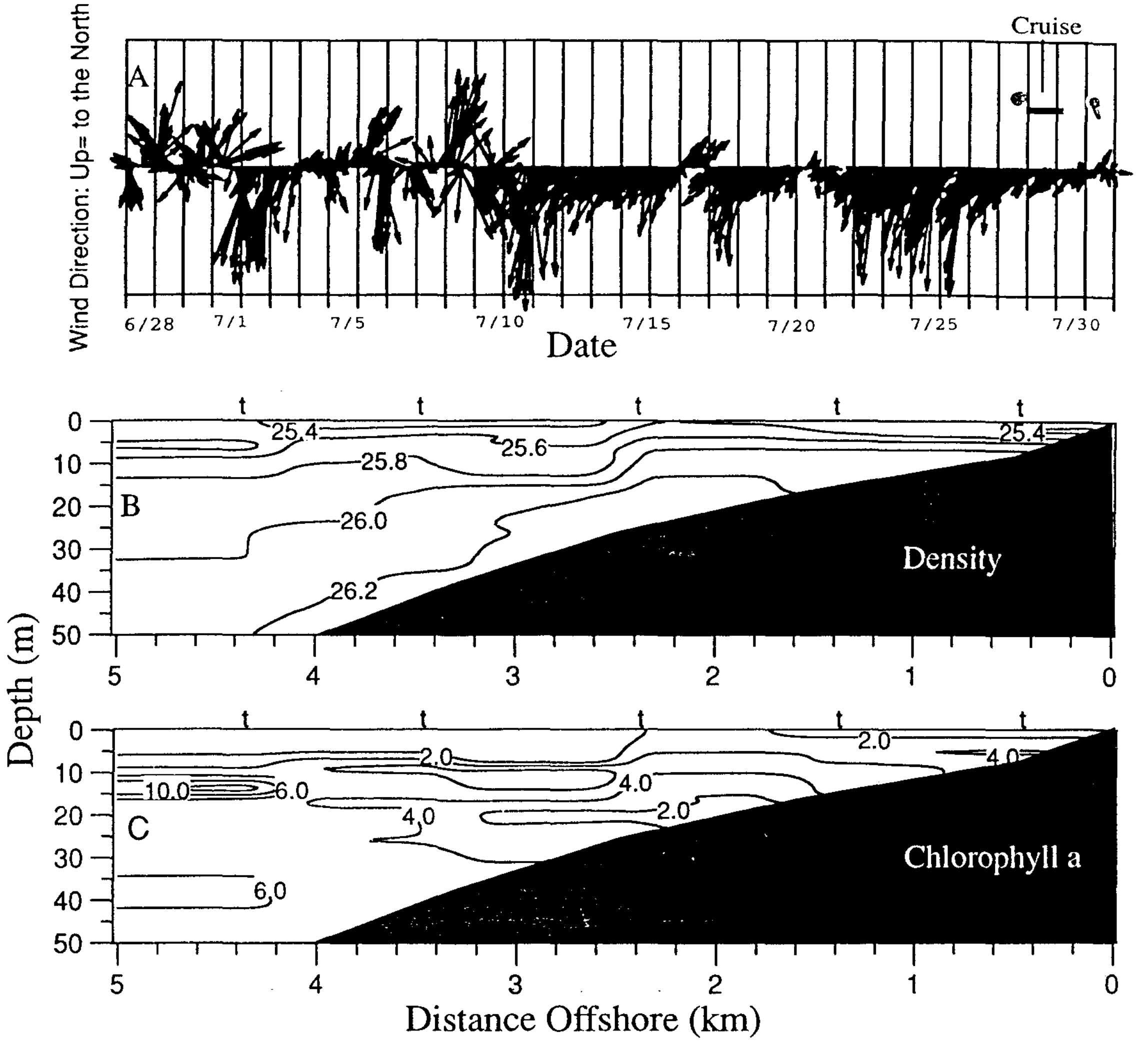


Figure 16: Nearshore Transect #2 July 29, 1997; A) Wind vector plot (m/s), B) Density (sigma-t), and C) Chlorophyll a (mg/l), contour plots

nearshore transects were virtually horizontal (Figures 12b-16b). In all of the transects, the surface waters of the stations closest to shore were dense (25.5 sigma - t). The nearshore surface waters of Shelf Transect #3 were slightly less dense (25 sigma-t) than those of transects #2 and #4. The chlorophyll a distribution of Shelf Transect #2 and #4 exhibited two areas of higher chlorophyll a concentration, one located at ~ 20 m depth at the 2.5 km stations and the other located at the same depth at the 25 km station. The chlorophyll a in the Nearshore Transects #1 and #2 was located in a subsurface band corresponding to the waters with a density of the permanent pycnocline (25.5 - 26 sigma -t). *Pseudo-nitzschia* spp. cells were only present in the samples from stations closest to shore at depths corresponding to the chlorophyll a maxima. In samples from the stations further offshore, no *Pseudo-nitzschia* spp. cells were seen.

Category 3 Relaxation

Nearshore Transect #3 November 11, 1997

Transect #3 was sampled late in the year after the upwelling season had come to an end. Prior to this transect the winds, from Nov 1 - 10, were predominantly southwesterly at 3 - 10 m/s. The winds, although variable had been southwesterly for the majority of days in the previous month.

Isopleths of temperature, salinity, and density were essentially horizontal (Figure 17). Density ranged from 24.4 - 25.4 sigma -t indicating that the permanent pycnocline was at depths greater than those sampled. The highest chlorophyll a levels were located at ~ 15 m depth at the stations furthest from shore. Overall chlorophyll a levels were low (0.6 - 1.4 μg/l) and highest concentrations were in the surface layers of

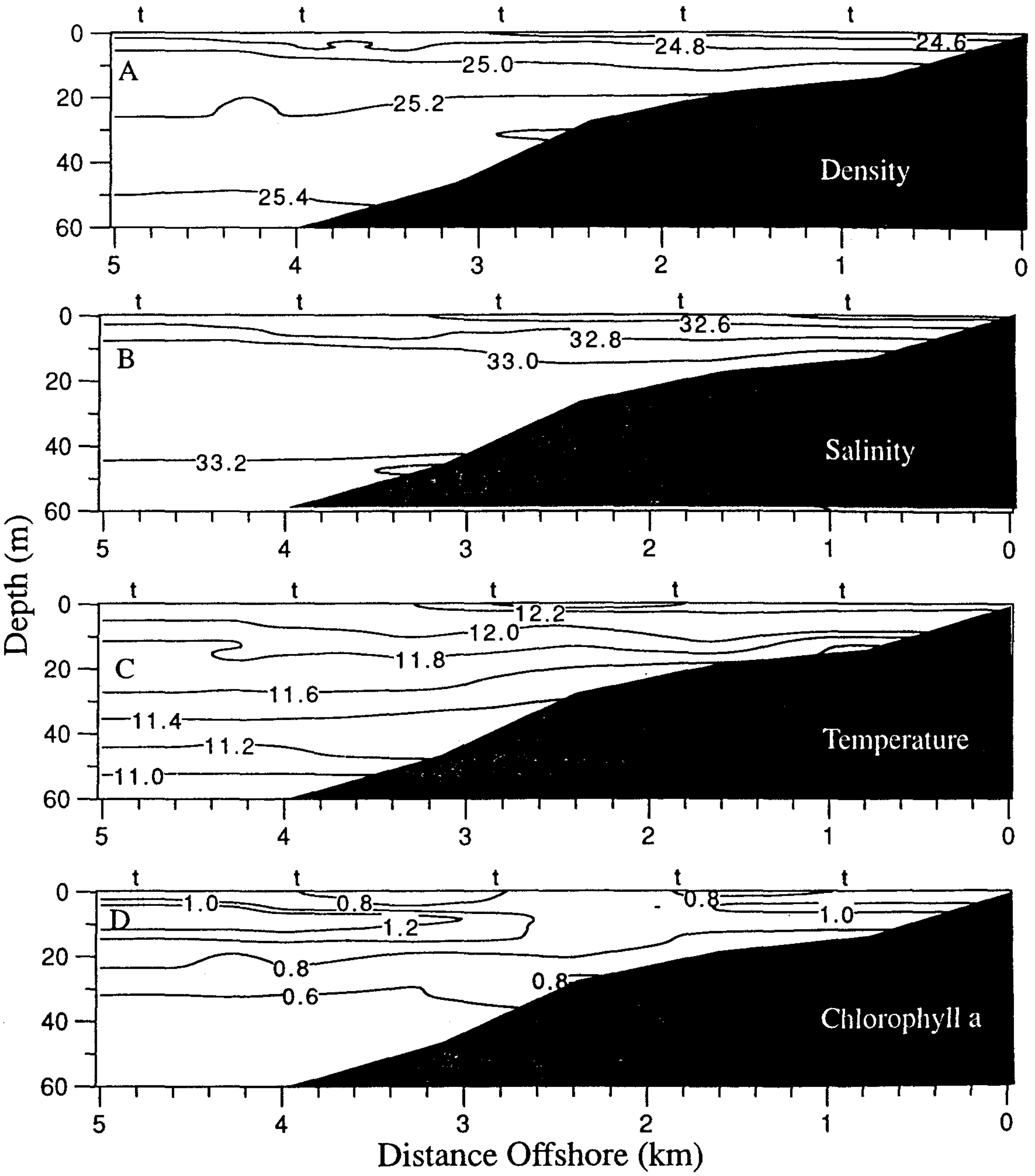


Figure 17: Nearshore Transect #3 Nov 5, 1997; A) Density (sigma-t), B) Salinity (psu), C) Temperature (C), and D) Chlorophyll a (mg/l) contour plots

the water column at all stations. There were very few *Pseudo-nitzschia* spp. cells in any of the samples.

Discussion

A number of studies have attempted to explain the chlorophyll distribution associated with the various oceanographic conditions found along the Oregon coast. As mentioned in the introduction, the coastal circulation has been extensively studied and described. Phytoplankton, by definition, are at the mercy of the currents and therefore the same physical interactions which determine the water column characteristics also determine the phytoplankton distribution.

Based on the distribution of chlorophyll a and zooplankton, Peterson et al. (1979) proposed a two-celled upwelling circulation model. Briefly the two cells lie on opposite sides of a divergence zone located ~10 km from shore. The nearshore cell rotates clockwise while the offshore cell rotates counter-clockwise. Peterson et al. (1979) described the chlorophyll a distributions for three oceanographic regimes, active upwelling, relaxed upwelling (relaxation), and transition from relaxed to active upwelling (spin up). During active upwelling, newly upwelled water, near the coast, is low in chlorophyll a. Further offshore low concentrations of chlorophyll a were found beneath the thermocline. The highest concentrations of chlorophyll a were located in the upper 10 m of the water column within or immediately seaward of the divergence zone (~10 km offshore).

During relaxation events, Peterson et al. (1979) found high chlorophyll a concentrations in the nearshore region (0- 12 km) with highest values in the surface waters < 10 km offshore. In a transect, after upwelling had ceased for 10 days, a strong seasonal pycnocline had developed. Chlorophyll a concentrations were highest adjacent to shore and distributed as a tongue within the permanent pycnocline.

Chlorophyll a distributions just after the transition from relaxed to active upwelling were characterized by two maxima located on either side of a divergence zone ~ 7 km from shore. Peterson et al. (1979) suggested newly upwelled water had split a previously developed bloom into two patches.

Small and Menzies (1981) evaluated data from transects sampled during 1972-1974 and characterized the chlorophyll a distributions during two steady states, strong and weak upwelling, and two transition states (spin up and spin down). During strong upwelling, water from the permanent pycnocline (25.5 - 26 sigma -t) intersected the sea surface at ~ 10 km offshore. Two separate patches of high chlorophyll a concentrations were observed, one centered just shoreward of the intersection of the permanent pycnocline with the sea surface and the other beginning about 25 km offshore. The water immediately adjacent to shore contained low chlorophyll a concentrations. During weak upwelling, the chlorophyll a distributions exhibited only one area of high chlorophyll a concentration. Under these conditions however, the location of the patch was shifted shoreward. When upwelling was very weak the permanent pycnocline often did not break the sea surface, in which case the chlorophyll a concentrations were highest against the coastline. In the spin up transition state, chlorophyll a distributions were similar to the upwelling steady state distributions with almost no chlorophyll a nearshore and two patches offshore. During the spin down transition state (e.g., relaxation) chlorophyll a distributions were similar to that observed during weak upwelling, except the chlorophyll a concentrations tended to be higher.

To summarize the work of Peterson et al. (1979) and Small and Menzies (1981), during strong or active upwelling two patches of high chlorophyll a concentration develop on either side of a divergence zone (~ 10 km offshore) generated by the upwelling of the permanent pycnocline. During relaxation or weak upwelling a single patch of high chlorophyll a develops close to shore. The two transitions states foreshadow the distributions that develop, with spin up being similar to strong upwelling and spin down being similar to weak upwelling or relaxation.

In the present study, the physical characteristics of the nearshore (0 - 5 km) and slope (2.5 - 30 km) transects were grouped into three distinct classes: a) early upwelling (spin - up), b) early relaxation, and c) relaxation. The classification was based on the winds that preceded the sampling and the physical characteristics of the water column during sampling. Each of these groupings exhibited distinct patterns of phytoplankton distribution.

Shelf Transect #1 was characterized as early upwelling (spin-up). Prior to the cruise the winds had recently shifted to northwesterly, upwelling favorable, after a week of variable winds (Figure 11a). The nearshore waters on this transect were from above the permanent pycnocline and of a density (24.4 - 25.4 sigma -t) which indicated the early stage of this upwelling event. Under conditions of active upwelling, the permanent pycnocline (25.5 - 26 sigma -t) intersects the sea surface ~ 10 km offshore, the region shoreward of this consists of upwelled water from below the permanent pycnocline and is more dense (Collins 1964). The chlorophyll a distribution was characterized by two areas of higher concentration, one located at 10 m depth at the station closest to shore (2.5 km), the other located along the seasonal pycnocline (~ 30 m) at the 30 km station (Figure 11c). Peterson et al. (1979) reported a similar chlorophyll a distribution along a transect sampled shortly after the transition from relaxed to active upwelling. They suggested that the phytoplankton bloom which had developed during the preceding relaxation had been split into two maxima by the actively upwelled water along a divergence zone centered 7 km from shore. A similar mechanism may have been at work during Shelf Cruise #1 in which a density front located at 11 km offshore split the phytoplankton bloom into two maxima. During our cruise, however, the density front was comprised of water from above the permanent pycnocline with a density of 24.4 - 24.9 sigma -t, while the density front discussed by Peterson was from the permanent pycnocline (25.5 sigma -t). The difference in the density of the fronts might be explained by the time of year as well as the winds preceding the sampling.

The samples analyzed by Peterson et al. (1979) were collected in July, during the middle of the summer upwelling season. Although a relaxation of upwelling had occurred just prior to their sampling, it is likely that the dense waters of the permanent pycnocline still remained over the continental slope and once upwelling recommenced the permanent pycnocline rapidly reached the sea surface. Shelf Cruise #1, on the other hand, occurred in October, late in the upwelling season. Mooers (1970) characterized this period as the Autumn transitional period between summer upwelling and the winter season. It is likely that by October winds had become variable enough to allow the permanent pycnocline to retreat to great enough depths that sustained upwelling winds would have been necessary to return it to the surface. Therefore, the winds acted on the less dense waters located over the shelf at the time of sampling and formed a density front of 24.4 - 24.9 sigma-t. In any case, the mechanism, implicated for the separation of the two chlorophyll a maxima, remains the same.

The next set of transects, Shelf Transects #2, #3, and #4 and Nearshore Transects #1 and #2, were classified as early relaxation. Each transect was preceded by northwesterly, upwelling favorable, winds which were decreasing in strength and had reversed direction by the time the transect was sampled (Figures 12a-16a). Although winds were downwelling favorable, the recent nature of the reversals had not allowed full relaxation to occur. The density of the surface water in the nearshore during all but one of these cruises was > 25.5 sigma -t, indicating that the source of the water was from the permanent pycnocline (Figures 12b-16b). Active upwelling is characterized by isopycnals of salinity, temperature, and density sharply sloping upward toward shore (Huyer, 1975). Additionally during active upwelling, the permanent pycnocline intersects the sea surface at ~ 10 km from shore. The isopycnals on these transects sloped only slightly upward toward shore and the permanent pycnocline intersected the sea surface < 5 km from shore. It seams likely that the wind reversal, shortly before the cruises, had allowed the density front, characteristic of active upwelling, to move from ~10 km offshore back to ~5 km offshore.

The chlorophyll a distributions during Shelf Transects #2-4 were characterized by two maxima, one located at ~10 m depth in the nearshore waters (0 - 5 km) and the other located at ~ 20 m depth at stations 20 - 25 km offshore (Figures 12c-14c). In Nearshore Transects #1 and #2 (0 - 5 km) the highest concentrations of chlorophyll a were found in a subsurface band at ~ 10 m depth (Figures 15c and 16c). This band of chlorophyll a was associated with waters of the permanent pycnocline and did not extend down into water denser than 26.0 sigma -t.

The existence of two chlorophyll a maxima separated by a region of low chlorophyll a is consistent with the distributions described by Small and Menzies

(1981), who found such distributions under strong upwelling conditions. In our results, however, the location of one of the two zones of high chlorophyll a was slightly different. The inshore patch reported by Small and Menzies (1981) was located ~ 10 km offshore, near the surface in the permanent pycnocline or just inshore of it. In Shelf Transects #2-4, both the permanent pycnocline and the inshore chlorophyll a patch were located closer to shore, only ~ 5 km from shore. Small and Menzies (1981) argue, based on the comparison of transects during relaxation, that the weaker the transition to relaxation the more the chlorophyll a distribution characteristic of strong upwelling is maintained. In our data, the nearshore location of the permanent pycnocline and the chlorophyll a maxima supports the characterization of these transects as early relaxation. Perhaps both of these features were initially being maintained further from shore by the upwelling favorable winds. Once the upwelling winds subsided or reversed to downwelling favorable, these waters and their associated phytoplankton moved back toward shore.

The progression of a relaxation event can be illustrated by comparing Nearshore Transect #2 on July 29, 1997 with Shelf Transect #3 July 31, 1997. Winds, which had been northwesterly prior to Nearshore Transect #2, weakened and reversed to southwesterly by Shelf Transect #3 (Figure 13a and 16a). Although the stations for these two transects were not identical, they did overlap at the 5 km station. A comparison of the data collected at 5 km reveals that the density of the surface waters had decreased from 25.5 sigma-t to 24 .8 sigma-t in the two days between sampling (Figure 13b and 16b). Presumably, the reversal of the winds had allowed the relaxation of the less dense offshore water back towards the shore. Halpern (1976) concluded that the time scale for a coastal upwelling event was 1 to 3 days from the onset of upwelling favorable or unfavorable winds to the arrival of dense or less dense water at the sea surface. Small and Menzies (1981) described a relaxation event which changed the near surface distributions of phytoplankton in one day.

The third classification, relaxation, was used to describe Nearshore Transect #3. The winds preceding the cruise were predominantly from the southwest at 3 - 10 m/s. The isopycnals during this cruises were nearly horizontal. The density ranged from 24.4- 25.4 sigma -t indicating that the permanent pycnocline had retreated to deeper water, further offshore (Figure 17). This transect occurred in November, a month characterized by Mooers (1970) as part of the winter season, during which the permanent pycnocline tends to be located below 50 m. Chlorophyll a was distributed throughout the surface layers in this transect, with a maxima located at ~10 m depth at the 5 km station.

According to the mechanisms described above, during relaxation, one would expect the highest concentrations of chlorophyll a to be immediately adjacent to shore. The distribution we observed suggests that the circulation pattern controlling phytoplankton distribution may differ during the winter season. Therriault (1978) showed that when wind velocities are over 5 m/s, physical processes dominate over biological and chemical processes in controlling the spatial variability of phytoplankton. Wind mixing undoubtedly had a substantial effect on the phytoplankton distribution during Nearshore Transect #3. Potentially, after waters had relaxed and become stratified, phytoplankton may have accumulated along the pycnocline. As the winter season continued, we would expect wind events to mix the phytoplankton to depths below the critical depth and the waters to become relatively depleted of phytoplankton. During periods of lower winds, enhanced or higher phytoplankton production might periodically occur.

The physical characteristics of the water column during the McArthur cruise AR - 98- 06 from May 28 to June 1 1998 indicated a condition of relaxed upwelling. The permanent pycnocline (25.5-26.0 sigma -t) was located at a depth of ~ 100 m at 32 km offshore and had risen to ~ 45 m at the 5 km station (Figure 3). At no point did the permanent pycnocline intersect the sea surface, a characteristic of active upwelling (Mooers 1976). The variable winds preceding the cruise had not established the upwelling circulation typically found along the Oregon coastal waters during the summer months.

Throughout the grid, the seasonal pycnocline (23.5-24.5 sigma -t) was located at a depth between 10-15 m (Figures 4-9). The horizontal orientation of the pycnocline again supports the "relaxed" condition of the coastal waters. Additionally, the presence of a seasonal pycnocline at such shallow depth indicates that the transition between spring and summer conditions had occurred. Mooers (1970) suggested that the spring season (March - May) was characterized by a permanent pycnocline at a depth of 70-100 m and the absence of a seasonal pycnocline. The summer season (June - August), on the other hand, has a permanent pycnocline at 40-60 m depth, and a shallower seasonal pycnocline at ~20 m. Previous to our sampling, solar heating and the absence of mixing due to strong wind events presumably had allowed the formation of the shallow seasonal pycnocline.

Nutrients measured during the McArthur cruise AR - 98- 06 indicated the permanent pycnocline separated the low nutrient surface waters from high nutrient deeper waters (Tables 1-4). This pattern of nutrient distribution is characteristic of stratified coastal waters in which the photic zone becomes nutrient depleted (Small and Menzies 1981). The lack of upwelling and limited wind mixing had not replenished the nutrients in the surface waters depleted by the primary production occurring in this layer. One exception to this nutrient distribution pattern occurred at the mouth of the Umpqua River, in which samples from the surface waters had elevated levels of silicate (Table 1b). The elevated levels of silicate corresponded with a low salinity lens of water presumed to have originated from the Umpqua River (Figure 7). Silicate levels in rivers might have been elevated due to terrestrial input.

During the McArthur cruise the highest chlorophyll a concentrations were located in the surface waters (0 - 35 m) of the nearshore stations (Figures 4-9). Moving away from shore, chlorophyll a concentrations decreased and the highest concentrations were found at the depth of the seasonal pycnocline (20 - 30 m). At the stations furthest offshore (32 - 60 km) an additional chlorophyll a maxima was located at 30 - 40 m depth, below the seasonal pycnocline (20 - 30 m) yet above the permanent pycnocline (75 - 100 m). The two chlorophyll a maxima are reminiscent of the cross-shore chlorophyll a distribution found under condition of active upwelling. The high chlorophyll a concentrations found in the surface waters of the nearshore stations and the seaward extension of chlorophyll a along the seasonal pycnocline perhaps suggest a zonal dispersion of phytoplankton from a previously formed patch. Small and Menzies (1981) point out a similar zonal extension from a nearshore patch in samples from a transect done during a relaxation event, in which there was a pronounced seaward extension of the 2 µg/l chlorophyll a isopleth. Peterson et al. (1979) found a similar distribution of chlorophyll a during a relaxation event, described as "a tongue with its hyoid in [the nearshore surface waters]". The circulation during relaxation, proposed by Peterson et al. (1979), suggests the shoreward flow of surface waters from > 10 km offshore. The water moving onshore covers the previous surface waters of the nearshore and creates a compensatory seaward flow below 10 m. The phytoplankton distribution exhibited by our data are consistent with the seaward advection of a nearshore chlorophyll a maxima along the seasonal pycnocline.

In comparison to the southern grid lines (transect lines CBG1-4), the two northernmost grid lines (transect lines CBG5 and CBG6) exhibited a slightly different distribution of chlorophyll a at the nearshore stations. CBG 5 and CBG 6 exhibited a thin surface layer (0-5 m) of elevated chlorophyll a concentration separated from the chlorophyll a maximum at 20-30 m depth (Figures 8 and 9). The winds, during the sampling of these two gridlines had reversed to northwesterly, upwelling favorable (Figure 2). Under the circulation model proposed by Peterson et al. (1979), the onset of upwelling is characterized by a very thin surface layer (<5m) moving seaward balanced by shoreward flow at ~10 m depth. The shoreward moving flow receives water from a divergence located ~10 km offshore. If this model is in fact correct, the shoreward flow at 10 meters could be responsible for the separation of the nearshore chlorophyll a into the two maxima (0-5 m and 20-30m) seen in CBG 5 and CBG 6. The circulation proposed by Peterson could only exist for a short period because, as upwelling continued, the shoreward flow would lead to the accumulation of high phytoplankton concentrations directly next to the coast, in the zone of abundant light and nutrients (Small and Menzies, 1981). In fact, Small and Menzies (1981) data from strong upwelling steady state conditions indicate that nearshore waters contain relatively low amounts chlorophyll a.

In the samples from the Shelf Transects and the McArthur cruise the concentrations of *Pseudo-nitzschia* spp. were highest in the surface waters (0 - 30 m depth) at the stations closest to shore. The sole exception to this was in Shelf Transect #1, in which an additional patch of elevated *Pseudo-nitzschia* spp. concentration was located between 20 - 30 km offshore at depths of ~ 30 m. Shelf

Transect #1 was characterized as early upwelling, with a density front ~10 km from shore. The two *Pseudo-nitzschia* spp. maxima were on opposite sides of this density front. Both Peterson et al. (1979) and Small and Menzies (1981) described similar chlorophyll a distributions after the onset of upwelling following a relaxation event. They suggest the two maxima are created by the separation of a bloom, formed during the preceding relaxation event, by the newly upwelled waters ~10 km from shore.

In the other Shelf Transects (#2-4) and the McArthur cruise the offshore *Pseudo-nitzschia* spp. maxima was absent. These transects, characterized as early relaxation, had a different wind driven circulation in which upwelling winds had subsided or reversed. If, as suggested for Shelf Transect #1, upwelling had separated a *Pseudo-nitzschia* spp. bloom into two patches, a subsequent relaxation could concentrate the nearshore patch closer to shore as the waters relaxed against the coastline. The offshore patch would presumably also be transported back toward shore, however, this already less concentrated patch would be further diluted and dispersed by the relaxation and might therefore not appear in the samples. Small and Menzies (1981) note that when upwelling winds subside rapidly, chlorophyll a concentrations increase over a wide area and lose their distinct band like distribution. There are, however, limitations in resolving spatial structures of at scales of less than 10 km using conventional point sampling methods (Mackas et al., 1985) and therefore low concentrations of *Pseudo-nitzschia* spp. might have been missed by our sampling.

Although *Pseudo-nitzschia* spp. and other net phytoplankton were absent from the offshore samples, a chlorophyll a maxima was present at 30-40 m depth. The offshore chlorophyll a maxima we observed may have been composed of phytoplankton from smaller size classes. Legendre and Demers (1984) describe the pelagic environment as a mosaic of microhabitats in which different species have differential growth characteristics. If, as suggested, an upwelling event divides an existing bloom into two cores, the offshore core would now be located in a very different physiological environment than that which allowed the bloom to develop in the first place. A change or succession of species would be expected as the physiological characteristics of the water change. Further investigations through the course of upwelling and relaxation events would be necessary to fully understand the patterns of species distributions.

The presence of high concentrations of chlorophyll a in nearshore waters appears to be associated with relaxation events or perhaps the early onset of upwelling. Elevated concentrations of *Pseudo-nitzschia* spp. in the nearshore waters have been repeatedly documented over the past decade as well, and have resulted in the closures of commercial and recreational shellfisheries along the coast of Oregon (Wood and Shapiro, 1993) . The conditions associated with blooms of *Pseudo-nitzschia* spp. are generally characterized by warmer sea surface temperatures (13 - 14 °C), well stratified water columns, and waters relatively depleted of nutrients (<2 µm/l No^3) (Buck et al., 1992). Results from investigations by Waltz et al. (1994) also indicated that *Pseudo-nitzschia* spp. blooms occurred when waters exhibited warmer temperatures (14.5 - 17.5 °C) and contained lower concentrations of nutrients (< 5 µM/l NO^3), generally indicative of post upwelling conditions. *Pseudo-nitzschia* spp. blooms have been reported under other conditions and undoubtedly factors other than temperature and nutrients play an important role in their development.

Fryxell et al. (1997) reviewed the occurrence of *Pseudo-nitzschia* spp., on the West Coast of the USA, during the period 1920 -1996 and discussed the relationship between *Pseudo-nitzschia* spp. abundance and ENSO (El Nino Southern Oscillation) events. ENSO events, occurring every 3 - 10 years, are characterized by the relaxation of the equatorial trade winds leading to, in the Eastern Pacific, elevated sea level and sea surface temperature. In higher latitudes the effects of ENSO are not as clearly understood, yet ENSO appears to decrease the intensity of the seasonal upwelling characteristically found in US West Coast waters. During ENSO warm events, *Pseudo-nitzschia* spp. abundances were generally high. Examples of high *Pseudo-nitzschia* spp. concentrations during ENSO events include Monterey Bay, CA in 1970, 1977, 1982, 1991, 1997, and Coos Bay, OR 1991 and 1997 (Malone, 1971; Garrison, 1979; Buck et al., 1992; Wood and Shapiro, 1994; Shanks pers. comm.). Our data for 1997, another ENSO warm year, indicated a dramatic increase in *Pseudo-nitzschia* spp. concentration over the previous two years. In 1995 and 1996, *Pseudo-nitzschia* spp. reached concentrations of 450 and 280 cells/ml, respectively. In 1997 cell concentrations reached as high as 850 cells/ml at stations near Coos Bay. It has been suggested that the growth strategies of some species of *Pseudo-nitzschia* spp. might be a possible explanation for its success during ENSO warm years (Fryxell, 1997).

During periods of rapid growth, *Pseudo-nitzschia* spp. cells in culture, were suspended until depletion of resources led to stationary phase (Fryxell et al., 1990). At this point, chains broke apart into singlets and doublets which sank to the bottom of the chamber. Upon addition of more nutrients, cells divided forming chains and resuspended into the water column of the culture vessel. Using these observations, and a detailed analysis of descriptions of a *Pseudo-nitzschia* spp. bloom by Allen (1932), Fryxell (1997) suggested that *Pseudo-nitzschia* spp. blooms, upon depletion of nutrients, may be able to sink, without loss of vitality, and exploit the nutricline and continue growth. This mechanism would suggest the existence of sequences of changing oceanographic conditions which would favor *Pseudo-nitzschia* spp. bloom development. Unfortunately, our sampling does not allow conclusions to be reached regarding the temporal occurrence of *Pseudo-nitzschia* spp. blooms. The results of our sampling does, however, suggests that, relative to other diatoms, higher concentrations of *Pseudo-nitzschia* spp. occur during post-upwelling conditions.

On the transects, adjacent to the mouth of Coos Bay, the highest concentrations of *Pseudo-nitzschia* spp. were located at stations closest to shore. Samples from the McArthur grid also indicate highest concentrations located at the nearshore stations in front of the mouth of Coos Bay. Several mechanisms may be responsible for elevated concentrations of *Pseudo-nitzschia* spp. found at the Coos Bay mouth. The permanent pycnocline, which reached its shallowest depth at the stations near the mouth of Coos Bay, separated the low nutrient surface waters from the high nutrient deeper waters. If, in fact, the growth strategies evoked by Fryxell (1997) are correct, the region where the permanent pycnocline was closest to the surface would be ideal for *Pseudo-nitzschia* spp. to exploit their competitive advantage. At these stations the permanent pycnocline rose to depths of ~45 m, most likely still in the photic zone. Perhaps, once the surface layers became nutrient limited, *Pseudo-nitzschia* spp. cells were able to sink down to the pycnocline and exploit nutrients available due to microscale mixing and continue growth. Other species of phytoplankton, with different growth strategies may have remained in the oligotrophic surface waters and become nutrient limited.

An additional explanation for the elevated *Pseudo-nitzschia* spp. concentrations found near the mouth of Coos Bay may be related to the estuarine plume generated by the ebbing tide. Yin et al. (1995) showed that the estuarine plume of the Fraser River was responsible for the entrainment of nitrate from the deep seawater below the plume. During flooding tide a salt wedge is formed by the deep seawater which has higher nitrate concentrations. The ebbing tide causes estuarine water to flow over this salt wedge and water from below is entrained. They also noted that a chlorophyll a maximum was commonly located at the base of the estuarine plume. Coos Bay discharges an estimated 53×10^6 m^3 of water during ebb tide (Arneson, 1976). As this water flows through the narrow channel at the mouth of the bay currents can exceed 1 m/s. It is quite possible that this water flowing into the nearshore could entrain nutrients from deeper waters in the area immediately adjacent to the mouth of the bay. This effect would be limited in scale to a few square kilometers, yet the twice daily occurrence could enrich this area, especially during times when the nearshore waters are stratified and nutrient limited. Under conditions of relaxed upwelling, coastal waters become stratified and eventually nutrient depleted. Tidal pumping at the mouths of estuaries may be a source of nutrients which could maintain phytoplankton populations in limited nearshore areas.

The simplest explanation would attribute the elevated level of *Pseudo-nitzschia* spp. near the mouth of Coos Bay as patchiness caused by non-uniform nature of relaxation events, in which parcels of water move cross-shore and along-shore at various rates creating a mosaic pattern. Under this explanation the location next to the mouth of Coos Bay would not have any causal significance. A final possibility would suggest that the *Pseudo-nitzschia* spp. bloom was actually occurring within Coos Bay and had appeared at the stations closest to the mouth after being transported there by ebbing tides. This last explanation is unlikely, and the following chapter will describe the experiments used to demonstrate that the *Pseudo-nitzschia* spp. blooms are, in fact, coastal and are transported into Coos Bay by the flooding tides.

In conclusion, we have found that, during conditions of relaxed upwelling, the highest concentrations of phytoplankton were located close to shore usually in the surface waters. Upon resumption of upwelling this nearshore bloom may be split in two by the newly upwelled waters and form a nearshore and an offshore band of higher chlorophyll a concentration located on either side of the upwelling front. When relaxation subsequently occurs the nearshore band appears to move shoreward and the offshore band may become more diffuse.

Pseudo-nitzschia spp. appears to be a common constituent of the nearshore phytoplankton. Highest concentrations were observed during post upwelling conditions characterized by elevated sea surface temperatures. Higher concentrations tended to be found near the coast under conditions of relaxed upwelling (Figure 10). High *Pseudo-nitzschia* spp. concentrations near the mouth of Coos Bay create the potential for tidal advection into the bay where sensitive shellfish beds are located.

Bridge

The preceding chapter discussed the relationship between the physical characteristics of the water column and associated phytoplankton distributions over the continental shelf with the preceding meteorological and oceanographic conditions. The distribution of toxic diatom *Pseudo-nitzschia* spp. was specifically addressed. Results indicated that the highest concentrations of phytoplankton were in the nearshore surface waters during conditions of relaxation following upwelling. High *Pseudo-nitzschia* spp. concentrations were found near the mouth of Coos Bay especially under post-upwelling conditions.

The next chapter will address the physical characteristics and associated phytoplankton distributions within the Coos Bay estuary. A variety of studies were carried out in order to test two hypotheses: 1) *Pseudo-nitzschia* spp. in Coos Bay are from nearshore coastal blooms. 2) Circulation within Coos Bay transports the *Pseudo-nitzschia* spp. over commercilly and recreationally harvested shellfish beds.

CHAPTER III

TRANSPORT AND DISTRIBUTION OF THE TOXIC DIATOM *PSEUDO-NITZSCHIA* SPP. IN THE COOS BAY ESTUARY

Introduction

Estuaries have received a tremendous amount of attention over the past fifty years and their ecological significance has been repeatedly documented. Based on their geomorphology estuaries can be classified into four categories:1) drowned river valleys, 2) fjord-type estuaries, 3) bar-built estuaries, and 4) tectonically produced estuaries Pritchard (1967). Circulation within an estuary is typically controlled by one or more of the following :a) differences in water density, b) the tides, and c) the winds (Day et al., 1989). The most basic description of estuarine circulation was a two layered circulation with net outflow of fresh water in the surface layers and net saline inflow in deeper layers (Pritchard, 1967). More recent studies have shown that current patterns can be much more complex and have many separate modes such as three layered circulation or discharge circulation with outflow at all depths (Elliott, 1976). The picture becomes even more complex if one considers the coupled circulation between the estuary and the adjacent shelf. The influence of coastal waters on the estuary is not limited to the tidal exchange, but includes factors such as alongshore winds (Wong and Garvine, 1984) and low frequency estuarine gravitational circulation (Masse, 1990). The primary purpose of our investigation was to look at tidally influenced circulation of nearshore shelf waters and their associated biota on

Coos Bay. Specifically the distribution of the toxic diatom *Pseudo-nitzschia* spp. was investigated over a complete tidal cycle and under various meteorological and oceanographic conditions.

Site Description Coos Bay

Coos Bay is the largest estuary entirely within Oregon and the fifth largest in the Pacific Northwest. It is located at the edge of the California Current, the eastern boundary of the North Pacific gyre. Seasonally, northwesterly winds result in the upwelling of cold, high salinity, nutrient rich bottom waters and the increase in nutrients leads to high primary productivity and dense phytoplankton blooms. These coastal waters and their associated biota are advected into Coos Bay with the daily tides. Coos Bay supports a rich and diverse filter feeding community and is the site of extensive commercial and recreational fisheries. These fisheries are an economically important resource to the local and regional community. The fisheries resources include dungeness crab (*Cancer magister*), pacific oyster (*Crassostrea gigas*), cockles (*Clinocardium nuttallii*) gaper and beefsteak clams (*Tresus capax, Saxidomus giganteus*), along with a host of other invertebrates and fin fish.

The Coos Bay estuary covers approximately 2470 hectares and is fed primarily by the Coos River and secondarily by a variety of small creeks and sloughs (Figure 18). It is connected to the ocean by an inlet, approximately 300 m wide, fixed on its northern and southern boundaries by stone jetties. The bay is actively dredged to maintain a shipping channel with a minimum depth of 12 m. Channel width averages about 100 m, while the remainder of the bay consists primarily of broad shallow mud flats.

Based on its circulation and stratification, the Coos Bay estuary can be classified as a drowned river valley estuary. The changes in salinity and temperature throughout the water column are minimal for most sections of the bay. Strong tidal currents, in relation to river flow, are the physical processes dominating circulation in a vertically homogenous estuary (Bowden, 1967) such as Coos Bay. Horizontal variation in salinity and temperature from the mouth to the head, on the other hand, is much more dramatic, with a marked decrease in salinity and increase in temperature moving toward the head of the estuary.

The tides are mixed semidiurnal, with two high and two low waters of unequal height in a lunar day. Tidal heights range from -0.6 to 2.8 m relative to mean low water and the mean tidal range is 1.7 m (Oregon Dept. of Trans, 1983). Maximum tidal currents occur during spring ebb tides and in the deeper channels can exceed 1 m/s.

River flow into the Coos Bay estuary is dominated by input from the Coos River, which drains ~ 110,000 hectares. Maximum flow occurs in February and minimal flow occurs in late summer (August and September), with flows of 155.7 m^3/s and 2.55 m^3/s, respectively (Percy et al., 1974). The two other major contributors to Coos Bay, the South fork of the Coos River and the Millicoma River, also follow a similar seasonal pattern of flow.

The tidal prism (P_n), the volume of water draining from the estuary between high tide and the succeeding low tide, was calculated for Coos Bay to be 5.3 x 10^7 m^3 (Arneson, 1976). Ketchum (1951) defined an exchange ratio, which is the proportion of water removed during ebb tide, in which

$$r_n = P_n / P_n + V_n .$$

With P_n as the local intertidal volume (tidal prism) and V_n the low tide volume of the segment of the estuary. For Coos Bay, the exchange ratio equales 0.77 (Arneson 1976), indicating that 77% of the water within Coos Bay is exchanged during ebb tide.

The flushing time is defined as the time necessary to replace the freshwater within the estuary at a rate that is equal to the discharge of the river (Dyer 1973). For the lower segment of Coos Bay, extending 7.6 km from the mouth, Arneson (1976) calculated a summer flushing time of 9.7 days and 22.9 days for the segment extending from 7.6 to 17.3 km.

The South Slough arm of the Coos Bay estuary is located ~1.6 km from the mouth of the Bay (Figure 1). It experiences limited freshwater input from a number of small creeks and streams, with maximum runoff in February at 6.6 m^3/s and minimal runoff in August at 0.2 m^3/s (Pimentel 1986). The tidal prism, for South Slough, was estimated at 9.4×10^6 m^3(Harris et al. 1979). The resultant exchange ratio indicates that 48% of the water from South Slough is discharged during ebb tide (Pimentel 1986). The combination of a high exchange ratio and long flushing time underscore the extent to which Coos Bay and South Slough are influenced by tidal circulation. During the summer, the physical structure of Coos Bay and South Slough generally reflects the nearshore ocean waters advected into the bay by the daily tides.

The toxic diatom *Pseudo-nitzschia* spp. is a common constituent of the nearshore waters in the vicinity of Coos Bay (Chapter II). As blooms of *Pseudo-nitzschia* spp. are advected into the bay by the tides the commercial and recreational fisheries located within the bay are potentially exposed. A variety of studies were carried out to asses the physical characteristics of the Coos Bay estuary over a full tidal cycle and under various meteorological and oceanographic conditions. At the same time biological samples were taken to determine the distribution of phytolankton with a focus on the toxic diatom *Pseudo-nitzschia* spp. The results were analyzed to test two hypotheses: 1) *Pseudo-nitzschia* spp. in Coos Bay are from nearshore coastal blooms. 2) Circulation within Coos Bay transports the *Pseudo-nitzschia* spp. over the shellfish beds.

Methods

To investigate the transport and distribution of phytoplankton in Coos Bay in relation to the physical characteristics of the water column, three sampling programs were carried out. First, to determine the biological and physical composition of the water entering the bay a transect of stations was established extending from the mouth of the bay to ~ 10 km into the bay (Figure 1). During the months of July and August 1997, under various meteorological and oceanographic conditions, these stations were repeatedly sampled on an incoming tide. Second, to investigate the biological and physical structure of the water column over a full tidal cycle, a 24 hour anchor station was occupied, from 8:00 AM May 27 to 8:00 AM May 28 1997. The station was located mid-channel, in the South Slough arm of the Coos Bay estuary ~ 2 km from the mouth of the bay. Lastly, in order to asses the extent of tidal incursion into Coos Bay, a tidal drift study was made on May 28, 1997. Coos Bay was divided into zones, each ~ 500 m in length (Figure 18). At slack low tide the R/V Bayrunner was piloted to a location at the mouth of Coos Bay (Zone A), just inside the jetties. The vessel was then allowed to drift with the currents as the tide began to flood. The motor was used only when necessary to keep the vessel in the channel. As the vessel drifted into each zone with the incoming tide, a variety of samples were collected.

At each station, and hourly at the 24 hour station, measurements taken included CTD casts, phytoplankton tows, and water samples. Additionally, at the 24

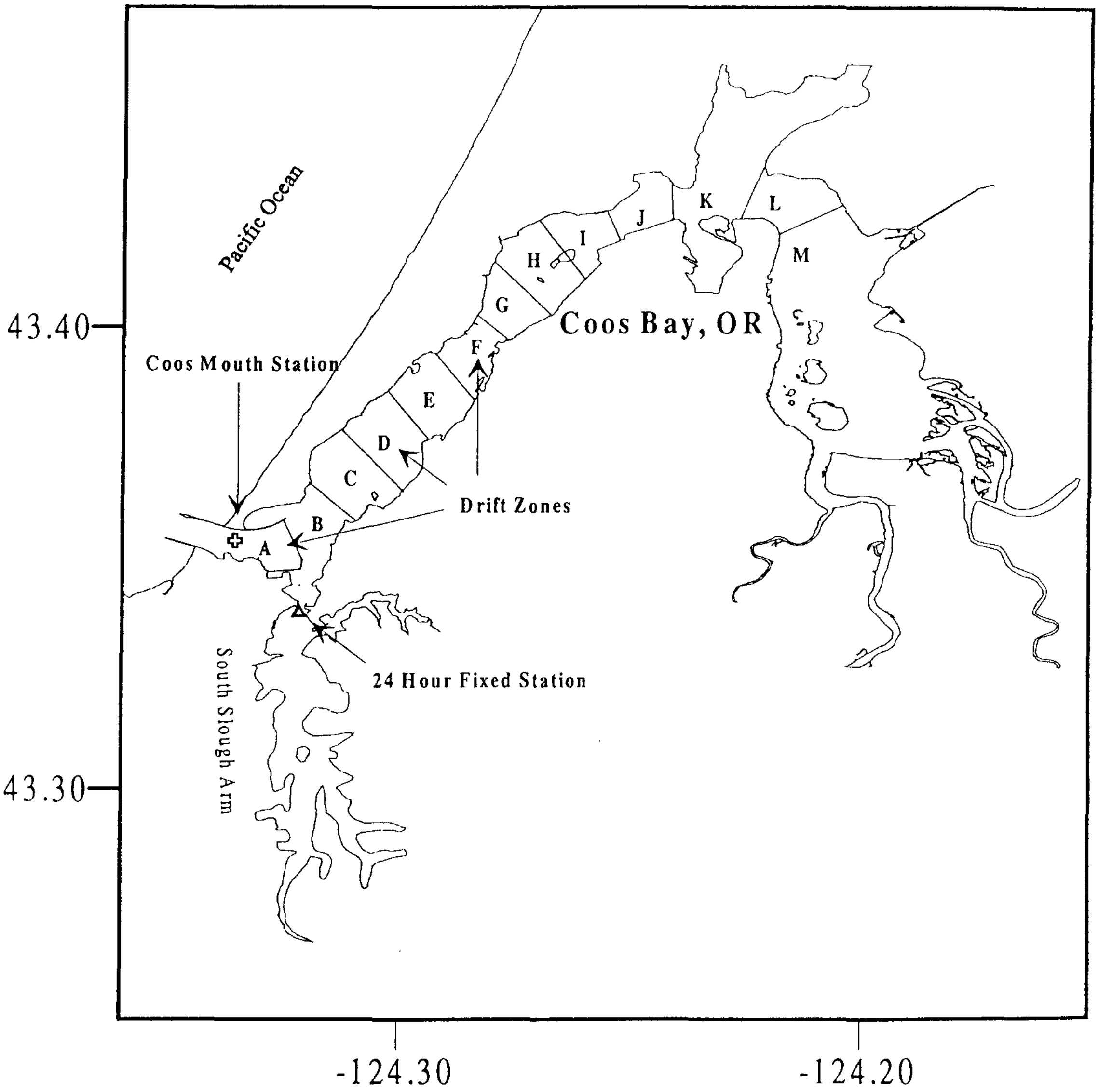


Figure 18: Map of sampling stations for Coos Mouth Station, 24 Hour Station, and Tidal Drift Study

hour station, the water 0.5 m below the surface was continuously monitored with a CTD. The CTD measurements were made with a SeaBird Electronics CTD with an attached Wetstar flourometer. During the drift study a YSI CTD meter was used to measure salinity and temperature. For all studies, the water samples were collected with a Niskin bottle from ~ 0.5 m below the surface and ~ 0.5 m above the bottom. A 250 ml subsample of the water was immediately placed on ice and frozen upon return to the lab for later nutrient analysis. Nutrient samples were sent to Lamont-Doherty Earth Observatory and analyzed using a QuikChem 8000 autoanalyzer (Lachat Instruments) for nitrate, phosphate, and silicate. Additional 250 ml subsamples of water were preserved with acidic Lugol's solution for later phytoplankton identification and enumeration. Upon return to the laboratory, 20 ml subsamples of the preserved phytoplankton samples were filtered and stained with Fast Green as described in Parsons (1985). The stained samples were then counted at 100x using a Leitz compound microscope. Phytoplankton was identified to genus and to species when possible. Wind data were obtained from the Cape Arago weather station located at 43° 20' 30"N and 124° 22' 30" W.

Results

In Bay Transects

During July and August wind conditions varied dramatically between sampling dates. A station, located at the mouth of Coos Bay was used to determine the physical characteristics of the nearshore water entering the bay with the incoming tide. Winds were predominantly from the NW, as expected during the summer upwelling season, but periodic reversals to winds from the SW, lasting from 1 - 7 days, occurred on several occasions (Figure 19 and 20). Results from the in bay transects were divided into two groups based on winds from the seven preceding days, and density and chlorophyll a concentrations of the water entering the bay.

Group 1 (Bay #s 2,3,4,5,6)

Group 1 transects were characterized by northwesterly winds while the water entering the bay was characterized by higher densities (> 25.5 sigma-t) and generally low concentrations of chlorophyll a (< 2.5 μg/l) (Table 2). The winds during the week preceding the group 1 transects were from the northwest with speeds between 1.5 - 8 m/s (Figure 19 and 20). The water entering the bay had a high density (> 25.5 sigma-t), indicating its source from within or below the permanent pycnocline (25.5 - 26 sigma-t). These waters also had low levels of chlorophyll (< 2 μg/l), again supporting recent upwelling, from below the photic zone, as their origin.

Group 2 (Bay #s 1,7,8)

Group 2 transects were characterized by weak variable winds or by southwesterly winds (Figure 19 and 20) and were associated with water of lower density (< 25.5 sigma-t) and higher chlorophyll concentrations (> 2.5 μg/l) entering the bay (Table 2). The wind speeds preceding the transects ranged between 1.5 - 8 m/s The lower density, of the flooding water, indicate its source was from above the permanent pycnocline (25.5 - 26 sigma-t).

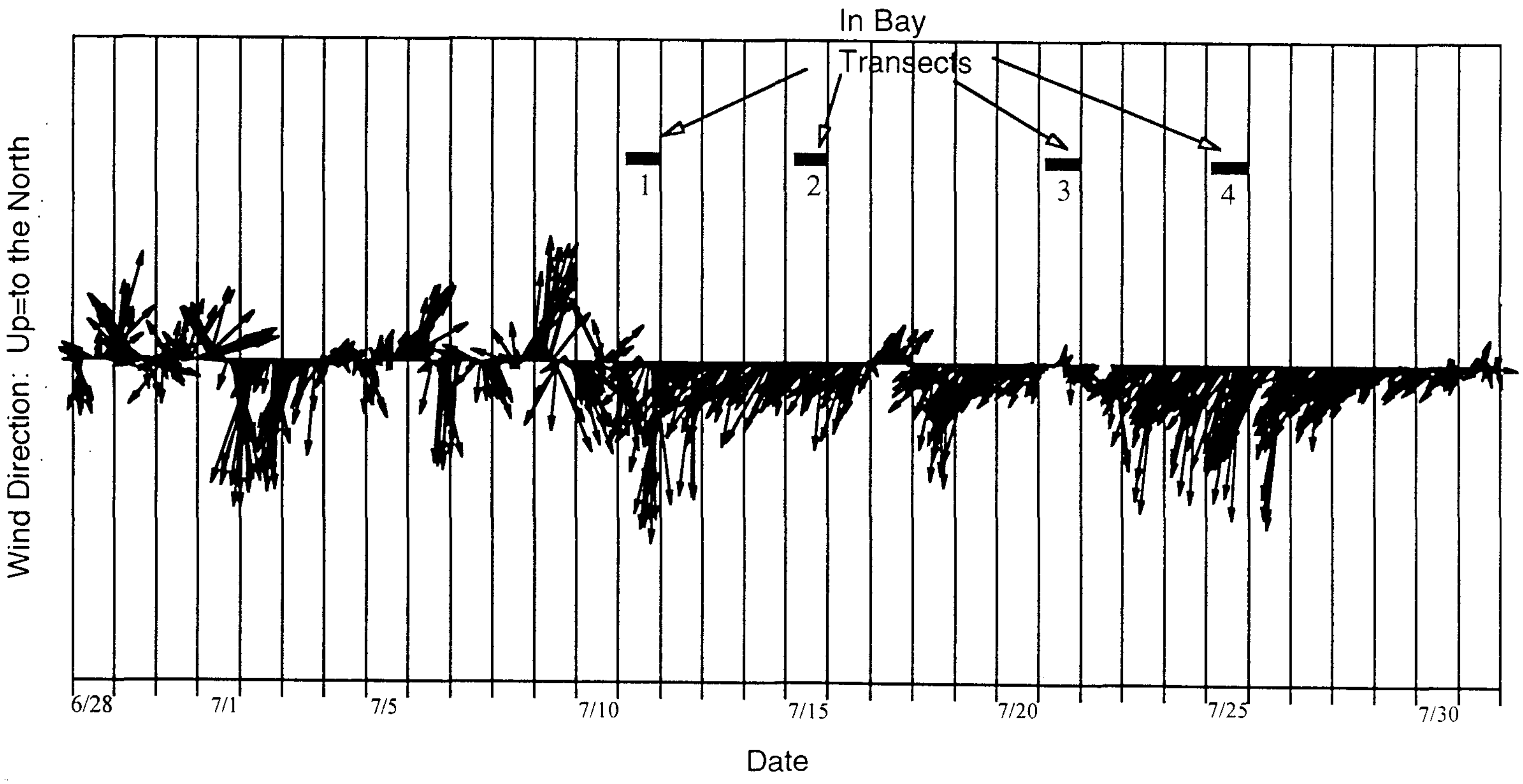


Figure 19: Wind vector plot for In Bay Transects #1-4, June 28 - July 31, 1997

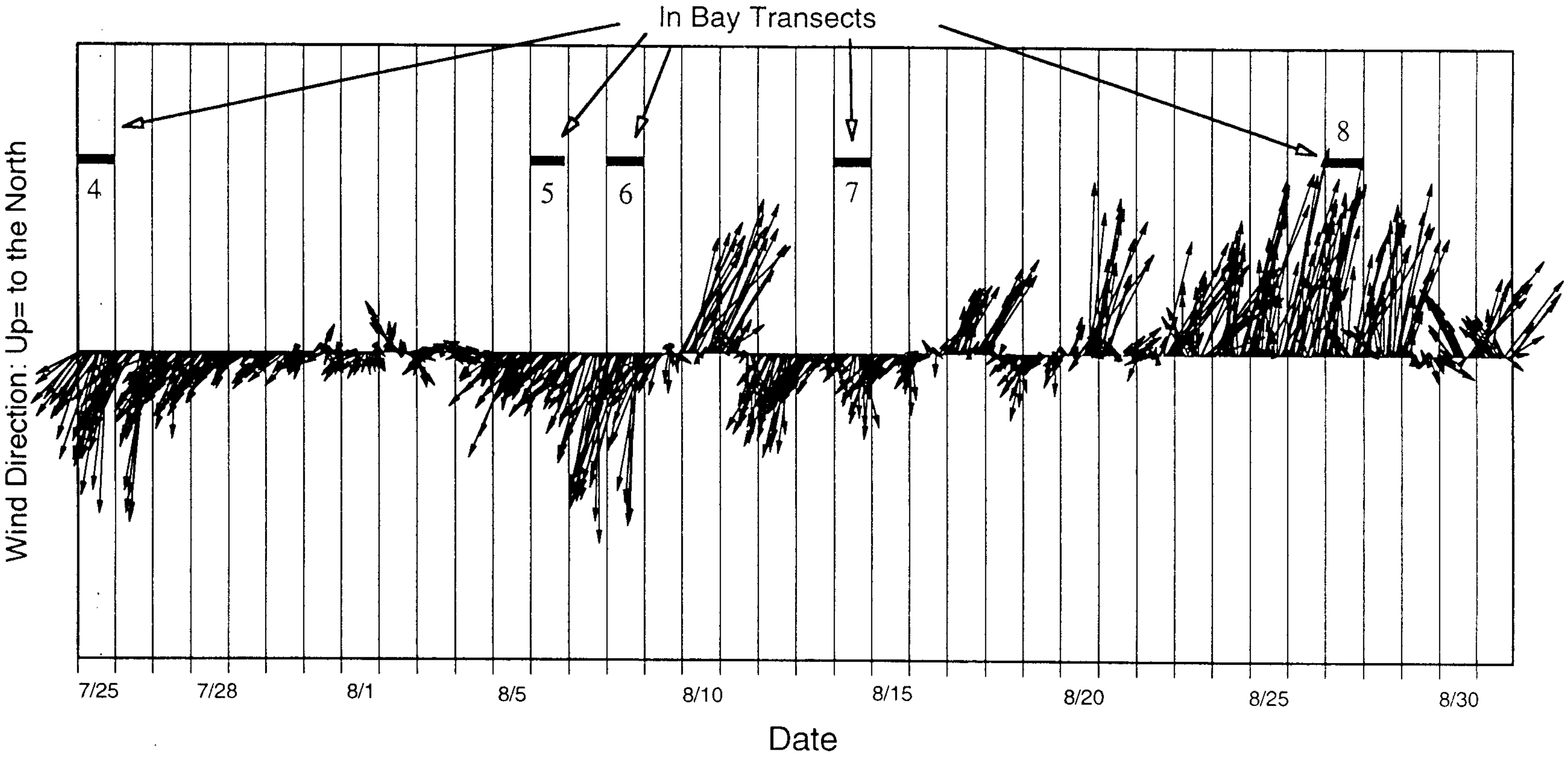


Figure 20: Wind vector plot for In Bay Transect #4-8, July 25 - Aug. 31, 1997

Table 2: In Bay transects Group 1 and 2 winds for preceding week, density,and ranges in chlorophyll a concentrations

Transect # Group 1	Preceding Winds	Density (sigma -t)	Chlorophyll a (ug/l)
2	Northwesterly	25.9	0-3
3	Northwesterly	25.8-26	0-0.09
4	Northwesterly	25.9-26.1	0-2.9
5	Northwesterly	25-27	0-0.35
6	Northwesterly	25.7	0-0.38
Group 2			
1	Variable	22.6-25	2-7.7
7	Weak Northwesterly	25.3	0.2-5.1
8	Southwesterly	23.5-23.6	1-2.6

24 Hour Anchor Station

The physical characteristics (e.g., temperature, salinity, and density) of the water, passing the 24 hour anchor station revealed a strong tidal signal. During the flooding tide, salinity and density increased while temperature deceased. A distinct front, demarcated by an accumulation of foam and buoyant particulates, delineated the intruding ocean water passed the station on the incoming tide. Once the tide reversed, salinity and density decreased while temperature increased until low tide was reached. There was not a distinct front noted during ebbing tide.

The phytoplankton concentration also followed a distinct tidal pattern. The different genera of phytoplankton, enumerated from the samples, were divided into two categories based on their concentration in relation to tidal height.

Category 1

This category of phytoplankton was associated with the incoming ocean water and reached highest concentrations during high tide or shortly thereafter (Figure 21). Category 1 included *Pseudo-nitzschia* spp., *Skeletonema costatum*, and *Eucampia* spp. In all three genera, samples from the surface and the bottom exhibited a similar trend, although absolute abundances did at times differ. *Pseudo-nitzschia* spp. can be used to describe the temporal pattern of abundance found for this category. The lowest concentrations of *Pseudo-nitzschia* spp. were found in the samples collected during the low tides. At low low water concentrations were ~ $2x10^3$ cells/l while at high low water concentrations were ~$1.4x10^3$ cells/l. Cell concentration increased as tidal height increased with low high water and high high water containing ~ $8x10^3$ cells/l and $1.3x10^4$ cells/l, respectively.

Category 2

The second category of phytoplankton appeared to reach highest concentrations shortly after low tide (Figure 22). This category included the genera *Stephanopyxis*, *Bacillaria*, and *Navicula*. For all three genera, highest concentrations were observed shortly after low low water, ~ 2 hours after the tide began to flood. As low high water was reached concentrations decreased to their minimum. During high low water, cell

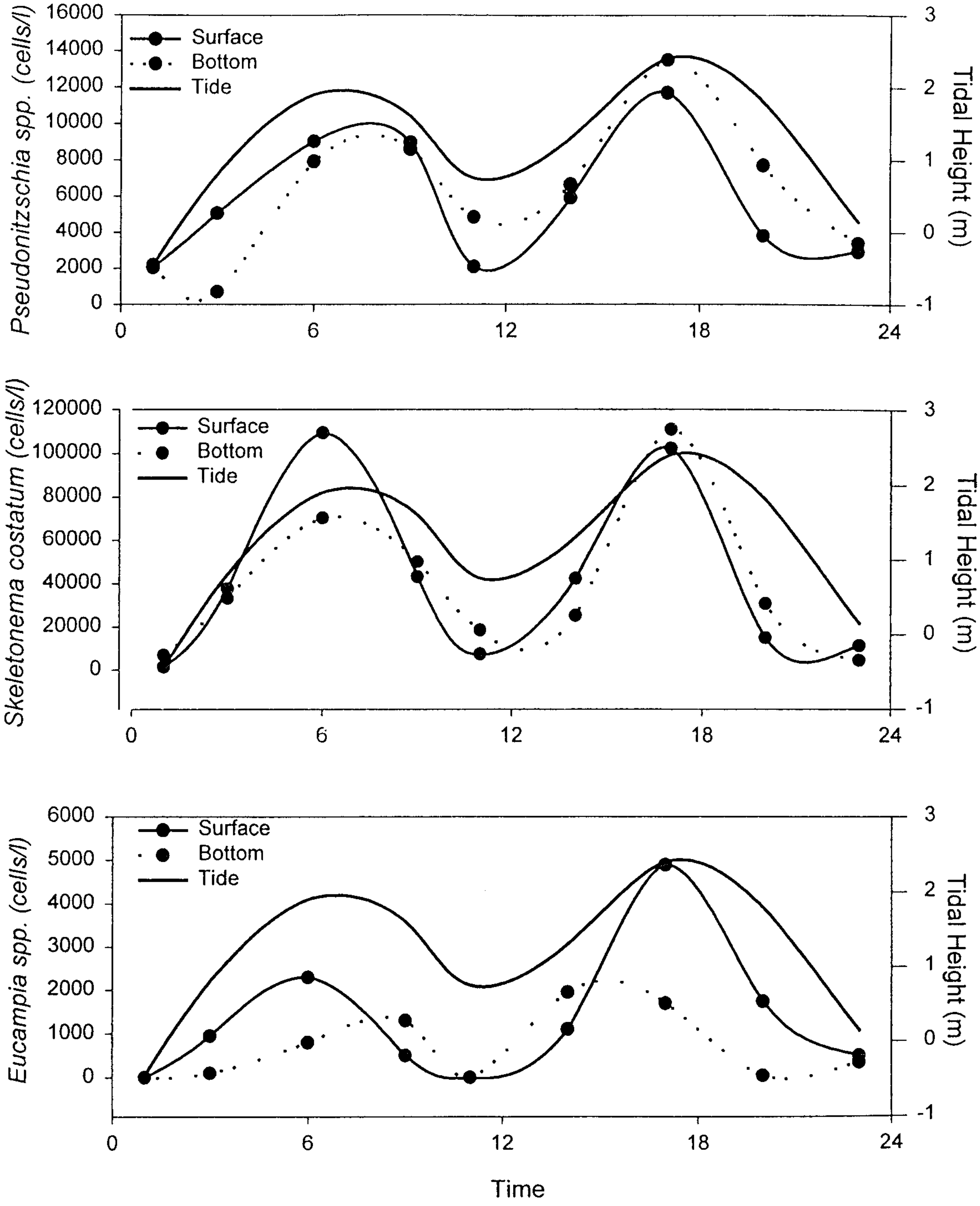


Figure 21: Category 1, phytoplankton associated with flood tide

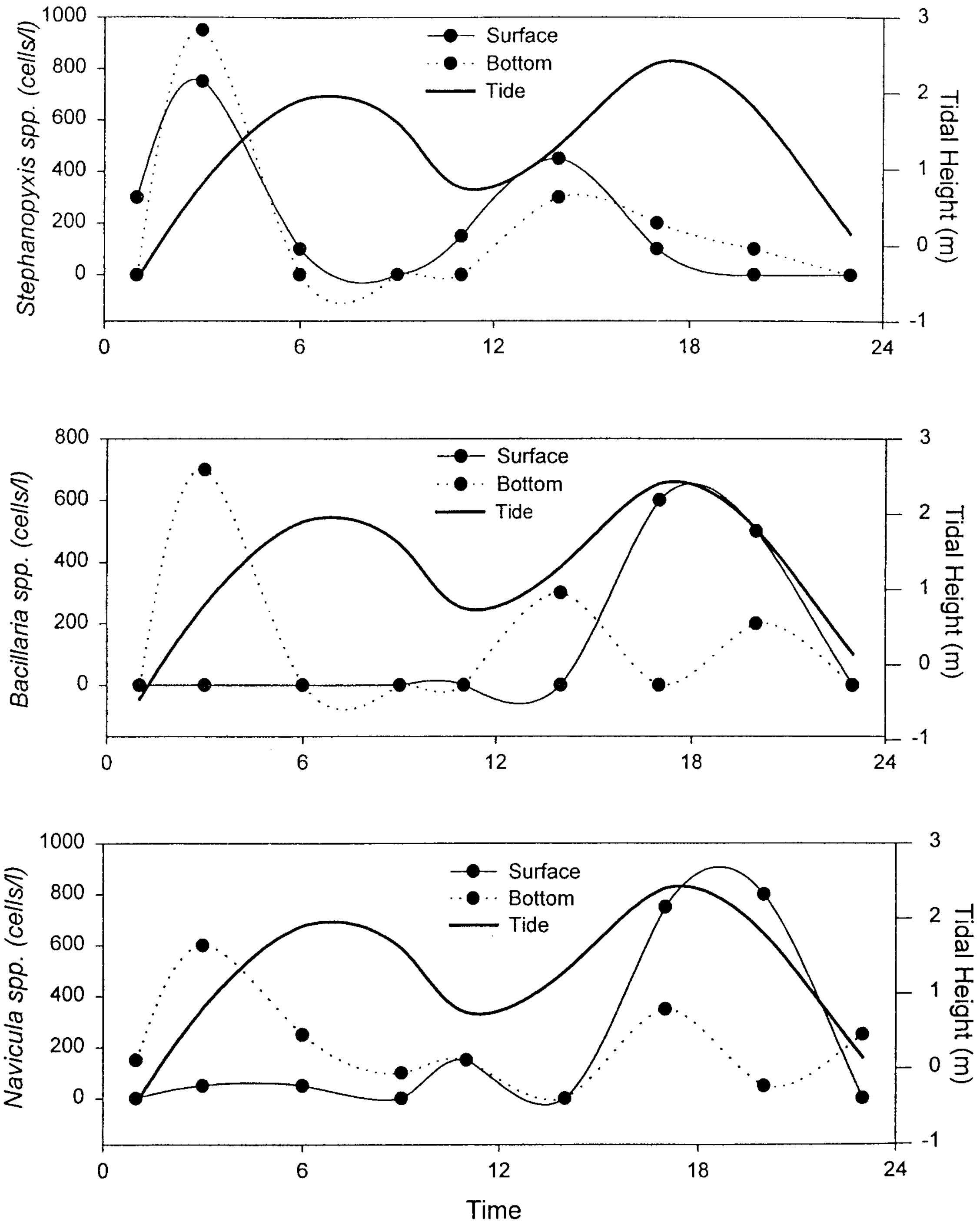


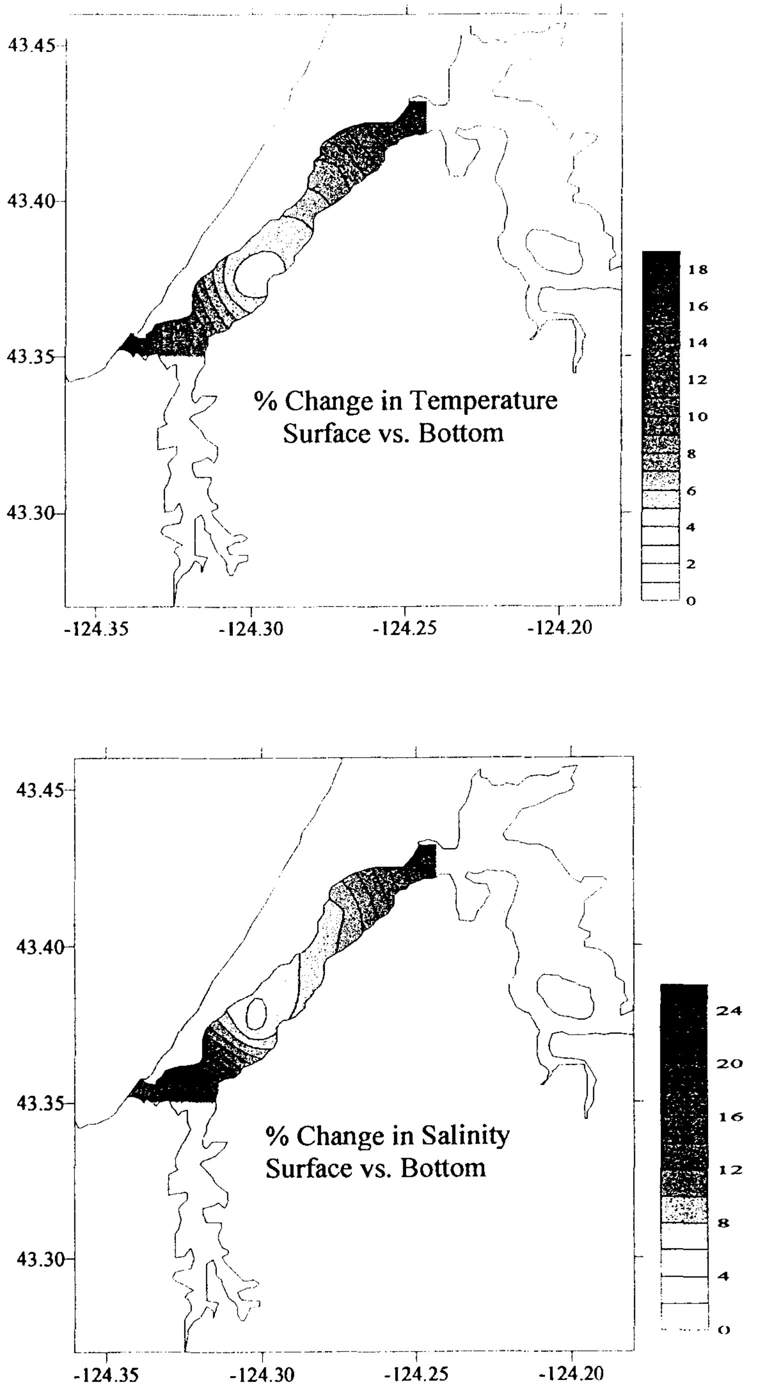
Figure 22: Category 2, phytoplankton associated with ebb tide

concentrations once again increased and a second, although lower, peak in abundance was seen ~2 hours after high low water. As the tide continued to flood, cell concentrations continued to decrease in both surface and bottom samples for *Stephanopyxsis*, while abundance of *Bacillaria* and *Navicula* only decreased in the surface samples. For these two genera, samples from the bottom had increasing cell concentration as the tide flooded to high high water.

Tidal Drift Study

The tidal drift study indicated roughly the extent to which the incoming tide travelled into Coos Bay during one flood tide. The vessel, which started in Zone A, near the mouth of Coos Bay, drifted with the flooding tide ~ 7.5 km into the bay reaching Zone J in ~ 6 hours (Figure 18). The physical characteristics of the water column changed with distance from the mouth of the bay (Figure 23). At the mouth of the bay, during the onset of flood tide, surface waters were less saline and warmer then waters at depth. Surface waters had a salinity of 24 psu and a temperature of 13.6 °C while water at 12 m had a salinity of 30 psu and a temperature of 12.2 °C. As the vessel drifted into Zone B this difference between surface and bottom waters remained evident. In Zone C the water column was well mixed, with a salinity of 30 psu and a temperature of 12.3 °C throughout the water column. The water column remained well mixed in Zones C-H. In Zones I and J, near the end of flood tide, surface water were once again less saline and warmer with similar ranges to those found in Zones A and B.

The distributions of individual species of phytoplankton followed two general patterns (Figure 24). In Zones A and B *Pseudo-nitzschia* spp. and *Skeletonema costatum* were less concentrated in the surface waters than in the bottom samples. In



% Change in Temperature Surface vs. Bottom

% Change in Salinity Surface vs. Bottom

Figure 23: Percent change from surface to bottom for A) Salinity and B) temperature during Tidal Drift Study

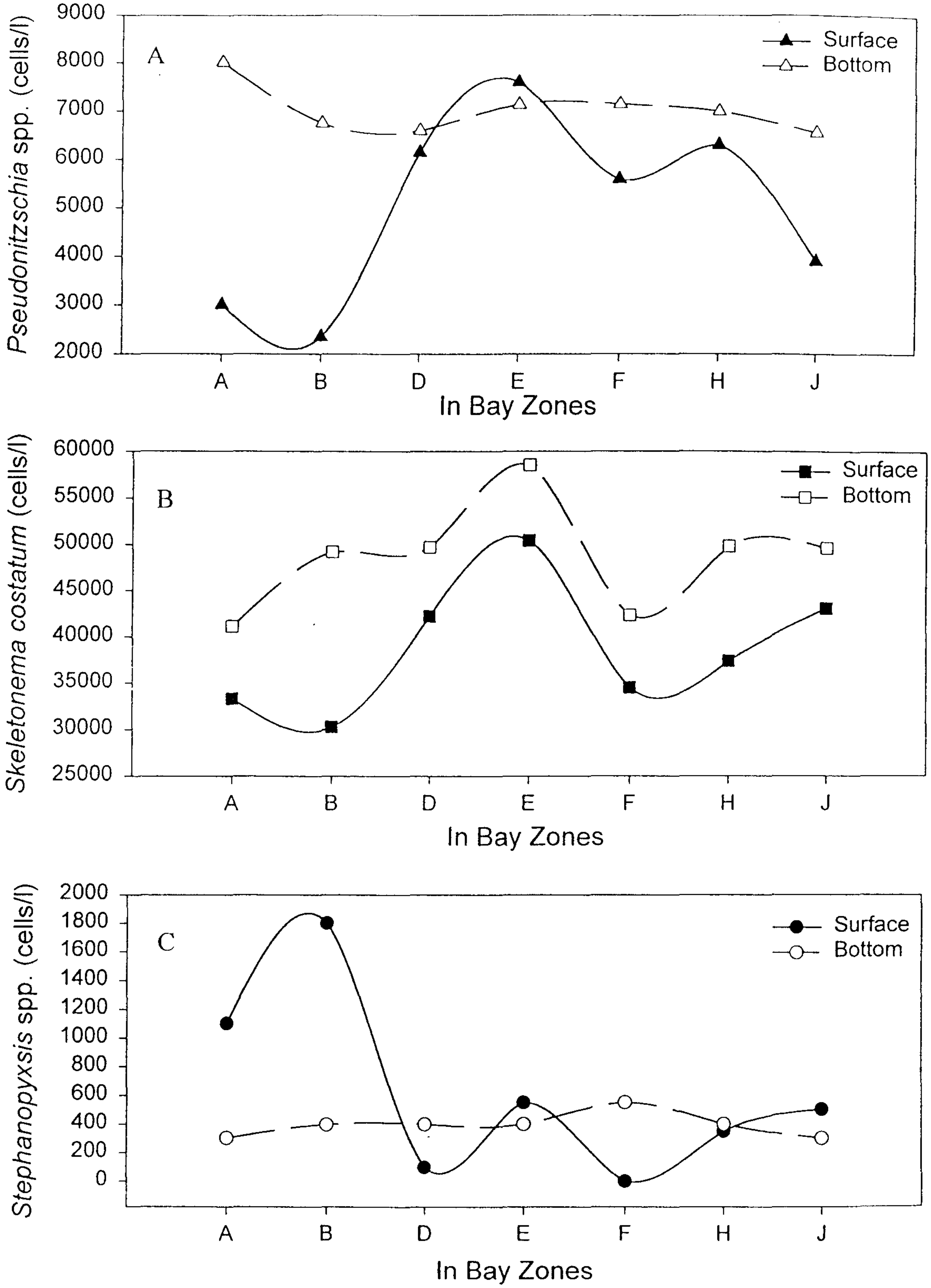


Figure 24: Phytoplankton concentrations during Tidal Drift Study

Zones C- H both species were relatively evenly distributed throughout the water column. In Zone J, surface samples again had fewer *Pseudo-nitzschia* spp. and *Skeletonema costatum* as compared to bottom samples.

The distribution of *Stephanopyxsis* spp. was quite different (Figure 24 c). For this species, the surface waters of Zone A and B contained the highest concentrations of cells. In Zones C-H the surface and bottom samples had similar concentrations although the concentrations were less than those found in the surface samples of zones A and B. In Zones H and J concentrations remained low and they were evenly distributed throughout the water column.

Discussion

The Coos Bay Estuary, during the summer months, is strongly influenced by the nearshore ocean waters which tidally flush the lower portions of the estuary twice daily. Our study attempted to characterize the degree to which the nearshore ocean affects the physical characteristics of the bay as well as the associated phytoplankton distribution found in the bay. The occurrence of potentially harmful algal blooms, specifically *Pseudo-nitzschia* spp. blooms, are common in the Oregon coastal waters. The extent to which commercially and recreationally harvested organisms are at risk of exposure to *Pseudo-nitzschia* spp. blooms is determined by the complex relationship between the nearshore and the estuary.

Transect samples, taken at the mouth of Coos Bay, were used to asses the biological and physical structure of the water entering the bay during flood tide. During upwelling favorable conditions, the nearshore coastal waters are dense and often poor in phytoplankton due to the waters recent upwelling from below the photic zone (Small and Menzies, 1981). Samples taken during upwelling favorable conditions indicated that dense nearshore water entered Coos bay with the flooding tide. In most cases, during upwelling conditions, the water column was well mixed and showed only a slight increase in salinity and decrease in temperature with depth (Table 2). Chlorophyll a concentrations were generally low throughout the water column, but if a peak existed it was located in the deeper layers (Table 2). The characteristics of the water entering the bay are similar to the conditions of the nearshore waters during upwelling.

Relaxation of upwelling occurs when the northwesterly winds cease or reverse direction and the warmer less dense waters, previously held offshore, relax back against the coast (Smith, 1976). On the transects during upwelling unfavorable conditions we found less dense water entering the bay with the rising tide. The transects sampled during upwelling unfavorable conditions, in general, contained higher chlorophyll a concentrations than the transects during upwelling favorable conditions (Table 2). The highest chlorophyll a concentrations were found near the bottom.

The vertically mixed, in temperature and salinity, nature of the water entering the bay suggests a single source or nearshore origin of the entire water column. A stratified water column, on the other hand, indicative of a two layered system was not seen in our samples. The density, of the water entering the bay, was higher in Group 1 (upwelling) than in Group 2 (relaxation). With only limited rainfall during the summer, the decrease in density between Group 1 and 2 must be attributed to nearshore oceanographic changes, such as upwelling or relaxation events. If in bay solar heating controlled the change in density exhibited at the mouth station, one would expect that when stations in the bay were warm, the density at the mouth would be low. Although substantial solar heating does occur over the shallow mudflats in the bay, the temperature of the water entering the bay was always cold during upwelling favorable conditions. In fact, water entering the bay was cold and dense at times when the upper bay temperatures were high (>16 °C). On the other hand, during relaxation events, water at the stations in the upper bay as well as those entering the bay were warm. Thus the water entering the bay is from the nearshore and reflects the oceanographic conditions found there.

The high exchange ratio, of 0.77 for Coos Bay, indicates that a large proportion of water in the bay is removed during ebb tide. During the summer months limited riverine input suggests the water removed to the nearshore will be replaced with water from the nearshore during the subsequent flooding tide. The extent to which the nearshore water flooding back into the bay is the same water which ebbed out of the bay is determined by nearshore mixing combined with alongshore currents. During the summer, alongshore currents are southward with velocities ranging from 8.6 to 26 km /day (Huyer et al. 1975). This suggests that the estuarine plume, developed during ebb tide, would be almost completely advected south of the mouth by the time flood tide resumed. The combination of a high exchange ratio, limited riverine input, and strong alongshore currents suggests that the majority of bay water is lost to the nearshore and replaced during each tidal cycle. Johnson (1982), using drift cards released in the mouth of a small estuary on the Oregon coast, concluded that there was nearly complete exchange of water between the lower estuary and the nearshore during each ebb / flood tide sequence. In fact, the drift cards had been carried 2 - 6 km southward before the start of the next flood tide.

Further indication of the extent to which the nearshore dominates the physical and biological characteristics of the water, in the lower reaches of Coos Bay, is indicated by the results of the 24 hour anchor station. The physical characteristics of the water passing the station showed a strong correlation with the tide. The phytoplankton community associated with flooding tide included *Pseudo-nitzschia* spp, *Skeletonema costatum*, and *Eucampia* spp. This community of phytoplankton were the same as those found most commonly in samples taken simultaneously in the nearshore waters by the NOAA ship McArthur (see Chapter 1). The concentrations of these phytoplankton was also similar to that observed in the nearshore waters. Comparing the community structure of flood tide to ebb tide, suggests that substantial mixing does occur because individuals from all genera are present in most samples. The dominance of nearshore genera, during high tide, however, clearly traces the nearshore origin of the waters entering with the flooding tide. The highest concentrations of *Pseudo-nitzschia* spp. were found in the flood tide samples supporting the hypothesis that *Pseudo-nitzschia* spp. develop in the ocean and are advected into Coos Bay with the tides.

For an endemic population of phytoplankton to develop within Coos Bay, a residence time of the water equal to or greater than the generation time of the species in the population would be necessary. Miller (1983) defines a "null point" in estuarine circulation, where the water present at higher high water fails to reach the mouth at lower low water and thus is returned upstream during the next flooding tide. As stated earlier, water that leaves the mouth of Coos Bay is advected away from the mouth by the alongshore currents and therefore does not return into the bay during the subsequent flooding tide. The exchange ratio, for the South Slough arm of Coos Bay, is 0.48, indicating that almost half the water in the slough is lost during each ebb tide. Only species with short generation times could possibly maintain a population within South Slough and even then a large percentage of that population would be lost to the nearshore. Ketchum (1954) defined the rate of reproduction necessary to maintain a population in an estuary despite continuous depletion by the circulation as:

$$k = -\ln (1-r)$$

Where k is the coefficient of reproduction and r is the exchange ratio of the estuary. For populations to be maintained in South Slough a coefficient of reproduction > 0.65 is necessary. This translates into a doubling time of < 1.09 tidal cycles. For Coos Bay proper, where the exchange ratio is 0.77, a coefficient of reproduction > 1.47 and a doubling time of < 0.48 tidal cycles would be necessary. Attached or benthic diatoms, on the other hand, could extend their residence time within South Slough and Coos Bay and do form endemic populations (Mutchler, 1998).

The first community of phytoplankton (Category 1), associated with flooding tide, was composed of genera that are typically considered coastal (Tomas 1995). They commonly are found in both marine and estuarine environments. The high concentrations of the phytoplankton, associated with the flooding tide, suggest these populations developed in the nearshore and were advected into the bay by the flooding tide (Figure 21). The low numbers present during low tide do not suggest that population growth is occurring in the estuary. It seems more likely that the remaining phytoplankton present, from category 1, during low tide are a result of tidal mixing which has occurred in the bay. The lower concentrations, found in the low tide samples, could be the result of dilution due to mixing with less concentrated estuarine water. This sort of dilution might follow the same mechanisms which control salinity dilution within an estuary. Undoubtedly, filtration by shellfish and other filter feeders, as well as settlement out of the water column, remove a substantial portion of the phytoplankton.

The second phytoplankton community (Category 2), associated with ebb tide, however, had concentrations that varied greatly during the tidal cycle (Figure 22). These genera are also present in the nearshore coastal samples but to a lessor extent. It is possible that this second community is maintaining its populations with production occurring in the estuary. For example, many species of *Navicula* are benthic and therefore may be reproducing on the mudflats in Coos Bay. The large amounts of substrate available at shallow depths, within the photic zone, create suitable habitat for many species not commonly found in deeper coastal waters. The limited concentrations of genera from this community, found in the nearshore samples, suggests that the primary source of these genera is not the nearshore environment.

The tidal drift study, which occurred at the same time as the 24 hour study and the McArthur nearshore grid, was used to determine the distance to which the flooding tide traveled into Coos Bay. The temperature and salinity profiles indicated a stratified water column in the first two zones (A and B), closest to the mouth, and a well mixed water column at zones further into the bay (C – H) (Figure 23). At the onset of flooding tide, nearshore water entered the bay at depth as a classic salt wedge. The salt wedge is probably short lived, however, and this structure moves up the bay as a front. Behind this wedge, the water column is well mixed, undiluted nearshore water as indicated by samples taken later during a flood tide.

Subsurface transport has been suggested as the mechanism responsible for transporting a red tide dinoflagellate from the mouth of the Chesapeake Bay to its bloom area in the upper bay (Tyler and Seliger, 1978). In this example, long range transport (240 km) was accomplished through entrainment into the more dense inward flowing bottom waters. In the upper-bay mixing in shallow areas was responsible for bringing the dinoflagellate into the surface layers. Although this transport was accomplished over many tidal cycles, the net inward flow of coastal water was not only responsible for maintaining the salinity of the estuary but transported organisms as well. On time scale of a single tidal cycle, flooding tides brought nearshore water, including the associated phytoplankton community, into Coos Bay.

Examination of the phytoplankton that entered the bay during the tidal drift study, suggested two general patterns of abundance. *Pseudo-nitzschia* spp. and *Skeletonema costatum* had the highest concentrations in the denser water entering the bay at depth in the two zones closest to the mouth (Zones A and B) (Figure 24). The surface waters, in these zones, had lower concentrations of both *Pseudo-nitzschia* spp. and *Skeletonema costatum*, again suggesting the source of both of these genera was the coastal nearshore waters. Once the vessel drifted to zones further into the bay (Zones C-H) the concentrations did not differ substantially between the surface and the bottom. The second pattern of abundance was displayed by *Stephanopyxsis* spp., which showed highest concentrations in the surface waters of Zones A and B (Figure 24). The high concentrations in the surface waters and the low concentrations in the bottom waters of Zones A and B , suggest this species might be a resident of Coos Bay. The vertically homogeneous concentrations of phytoplankton, in Zones C-H, support the idea that mixing is occurring at zones further in the bay.

This study only evaluated transport and circulation influenced by the diurnal tidal cycle. Other lower frequency physical mechanisms have been shown to influence the coupled circulation between the estuary and the adjacent shelf waters. Gravitational circulation drives surface low salinity estuarine water onto the shelf and pulls higher density, saline, near bottom shelf waters into the estuary (Masse, 1990). The gravitational circulation exists under both conditions of relaxation and downwelling. Under upwelling conditions, however, this gravitational circulation may be even stronger. Preliminary data, from current meters on the continental shelf and in Willapa Bay, Washington, indicate a gravity current of 10-20 cm/sec entering Willapa Bay (Hickey, pers. comm.). A current with such a velocity would travel ~10 km/day. Such low frequency circulation might be responsible for the large scale transport of phytoplankton.

In conclusion, the simultaneous nearshore and in bay sampling indicated the large degree to which the lower portion of Coos Bay is dominated by physical and biological characteristics of the nearshore water. The high estuarine exchange ratio combined with strong alongshore currents ensure that a large proportion of water entering the bay with the flooding tide are of coastal origin and not estuarine. The density, temperature and salinity of the water entering the bay varied with the upwelling and relaxation events. Chlorophyll a concentrations were higher during relaxation events than during upwelling events. Denser nearshore water entered the bay at depth and was rapidly mixed in the channalized lower bay. During flood tide, after a moving salt wedge entered, the water was well mixed undiluted nearshore water. *Pseudo-nitzschia* spp. entered with the flooding tides and did not appear to have populations endemic to the bay. The entering nearshore water penetrates ~ 7.5 km into the bay during one flood tide. Many of the commercial and recreational shellfish beds are located in this section of Coos Bay. These populations are at risk during harmful algal blooms occurring in the nearshore coastal waters of the Oregon continental shelf.

CHAPTER IV

CONCLUDING SUMMARY

The link between the estuary and the adjacent continental shelf is complex. This study has investigated the physical oceanography and phytoplankton distributions, in the Coos Bay estuary and the adjacent shelf, and the connection between these environments under various meteorological and oceanographic conditions. Particular attention was paid to the distribution of the toxic diatom *Pseudo-nitzschia*.spp.

Chapter 1 demonstrated that, under upwelling conditions, the nearshore waters (0 - 5 km) were derived from in or below the permanent pycnocline (25.5 - 26 sigma-t) and usually contained low concentrations of phytoplankton. During relaxation events, phytoplankton that had developed just offshore, were moved shoreward as a stable density structure was reestablished. Under conditions of upwelling relaxation, the highest concentrations of phytoplankton were found against the coast. The distribution of *Pseudo-nitzschia* spp. followed this general pattern; highest concentrations were observed in post-upwelling conditions where the nearshore waters were stratified, sea surface temperatures were elevated, and nutrients were low.

In Chapter 2, various studies examined the physical and biological oceanography of the Coos Bay estuary. The lower portion of Coos Bay (0 - 10 km) was dominated by the physical characteristics and phytoplankton populations of the nearshore coastal ocean. A high estuarine exchange ratio, limited riverine input, and strong alongshore currents combine to ensure almost complete tidal exchange of the estuarine water with the nearshore every flood / ebb sequence. *Pseudo-nitzschia* spp. entered the bay with the flooding tides and did not appear to have a population endemic to the bay. During a flood tide, nearshore waters penetrate ~ 7.5 km into the bay, reaching many of the commercially and recreationally harvested shellfish beds.

In the decade since the first reported outbreak of domoic acid poisoning, in Prince Edward Island, Canada, much has been learned about *Pseudo-nitzschia* spp. Species of this genus have been documented, at least since the early 1900's, as a relatively common constituent of the phytoplankton assemblage in the waters of the continental shelf of the West Coast of North America (Fryxell et al. 1997). More recently, blooms have been repeatedly documented in the waters off Northern California, Oregon, and Washington. Our study, as well as others, have indicated that higher concentrations of *Pseudo-nitzschia* spp. tend to be associated with post-upwelling conditions (e.g., higher sea surface temperatures, thermal stratification, and low nutrient concentrations) (Buck et al. 1992; Waltz et al. 1994).

Our understanding of the causes of domoic acid production by *Pseudo-nitzschia* spp. has progressed since the 1987 event in Canada. In the species *P. pungens*, domoic acid production has been attributed to silica limitation in the presence of abundant nitrogen (Bates, 1991). Domoic acid production was enhanced by a factor of ~ 3 by phosphate limitation (Pan, 1996). It appears that nutrient limitation may cause domoic acid production in certain species, but the precise conditions may vary between species. Garrison (1992) suggested that toxic events might be limited to seasons or locations where stratification and nutrient depletion occur.

During the summer, the characteristics of the water of the lower portions of the Coos Bay Estuary are dominated by the nearshore shelf waters. It stands to reason that the shellfish beds, located in the lower portion of the bay, are at risk from domoic acid intoxification when the nearshore conditions support blooms of *Pseudo-nitzschia* spp. that are producing domoic acid. The following scenario illustrates a potential sequence of events leading to shellfish toxicity with in Coos Bay. 1) Seasonal upwelling provides nutrient rich water to the nearshore region. 2) Phytoplankton blooms develop offshore of this newly upwelled water. 3) Upwelling winds subside, or reverse to southwesterly, and the phytoplankton blooms move back against the coast as the offshore pressure gradient subsides. 4) If the relaxation event continues, stratification and nutrient depletion of the nearshore waters might create conditions for a *Pseudo-nitzschia* spp. bloom and domoic acid production. 5) Nearshore populations of *Pseudo-nitzschia* spp. are advected into Coos Bay by the daily tides. 6) Shellfish and other filter feeders accumulate domoic acid. 7) Domoic acid enters the food web with wide ranging potential consequences.

The sequence described above is just one possible scenario, interruptions by the resumption of upwelling or mixing events due to wind may disrupt the chain of events. Additionally, the accumulation of domoic acid varies greatly between organisms feeding on *Pseudo-nitzschia* spp. Blue mussels, sea scallops, dungeness crabs, anchovies, and razor clams have all been shown to accumulate domoic acid (Bates, 1989; Wekell et al., 1994; Douglas et al.,1997). The differences in accumulation and subsequent depuration are illustrated by a comparison of mussels and razor clams. The blue mussel (*Mytilis edulis*), used as a sentinel organism by the Oregon Department of Health, rapidly accumulates domoic acid when present, but depurates within 2 to 3 days (Silvert, 1991). The razor clam (*Siliqua patula*), apparently depurates domoic acid over a longer period of time and, therefore, can become toxic through longterm low levels of exposure (Drum et al. 1993). The pacific oyster *(Crassostrea gigas*), commercially harvested in Coos Bay, can accumulate domoic acid but samples taken from the Willapa Bay estuary during coastal *Pseudo-nitzschia* spp. blooms did not reveal detectable amounts of domoic acid (Sayce and Horner, 1996). The various rates of accumulation and depuration add to the complexity of monitoring programs.

The state of Oregon has been monitoring for domoic acid since 1992. During the summer, six coastal sites are sampled 2 times per month. Most samples are from *Mytilis edulis*, but razor clam samples are analyzed when available. Sampling is increased if appreciable levels of domoic acid are detected (Deb Cannon pers. com.). The time between sampling and the reporting of the results of the analysis are in excess of one week. With the extended turn around time between sampling and harvesting closures the potential exists for significant toxic events to go undetected or to be reported after the public has been exposed. The high cost of field sampling and the dilution of resources due to monitoring for other harmful algal blooms, such as paralytic shellfish poisoning, make designing a comprehensive monitoring program difficult. Our current understanding of *Pseudo-nitzschia* spp. blooms, and the sequence of conditions leading to a higher risk of toxic events, suggests a schedule of sampling. Special attention should be paid during ENSO years, when warmer sea surface temperatures and coastal stratification are more common. When upwelling is intermittent or reverses, an assessment of the phytoplankton community for the presence of *Pseudo-nitzschia* spp. could serve as a preliminary warning. Further, during non-upwelling conditions, which might lead to nutrient limitation, monitoring should increase. Many aspects of monitoring could be carried out remotely, using existant weather stations and moorings, and expensive field sampling and testing should be reserved for times of elevated risk. Ideally, monitoring should move away from a reactive sampling program, which detects toxins after they are present, to a more predictive program which assigns risk levels based on the preceding oceanographic and meteorological conditions. Based on our findings, we suggest utilizing wind and sea surface temperature data to establish the coastal oceanographic conditions. During the upwelling season (April- October), when non-upwelling conditions arise, sample for *Pseudo-nitzschia* spp. near sensitive sites (eg. aquaculture shellfish beds and popular recreational shellfish beds). If *Pseudo-nitzschia* spp. are present, test for domoic acid in shellfish and other harvested filter feeders.

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