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MAJOR NUTRIENT DISTRIBUTIONS IN RELATION TO THE PHYSICAL STRUCTURE OF THE GULF OF ALASKA SHELF

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A

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ABSTRACT

The northern Gulf of Alaska is a biologically productive downwelling shelf. Nutrient sources supporting such productivity have not been adequately studied. Thirteen primary stations were occupied twelve times throughout 1998 and 1999 in an attempt to clarify nutrient distributions and sources. The shelf waters were warmer, fresher, lower in nitrate, and higher in phytoplankton biomass in the spring of 1998 compared to 1999. Nitrate, silicate, and phosphate were positively correlated with salinity indicating an offshore nutrient source. The largest rates of new production, estimated from nitrate drawdown in the upper layer between March and July/August, were 2.6 mmole nitrate m^{-2} day $^{-1}$ in 1998 and 1.9 mmole nitrate m^{-2} day $^{-1}$ in 1999. There was evidence of a summer onshore flux of dense, nutrient-rich bottom water when the downwelling regime relaxed or reversed. This seasonal flux was 20% less than the estimated nitrate flux through nearby Hinchinbrook Canyon.

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1. INTRODUCTION

1.1 Reasons for interest

The Gulf of Alaska (GOA) shelf appears to be a very productive region insofar as it supports several commercially important fisheries such as salmon, pollock, and halibut. However, the reasons for this high productivity are not understood, considering it is a deep, coastal downwelling shelf fed by nitrate-poor runoff. Nutrients and incident radiation and the presence of some stratification are all necessary for phytoplankton growth, which is the foundation of a productive ecosystem (LALLI and PARSONS, 1993). Other shelf regions at lower latitudes along the eastern edge of the Pacific Ocean support productive ecosystems due to wind-driven upwelling, which regularly replenishes the euphotic zone with nutrients from deep nutrient-rich waters. The GOA, on the other hand, only experiences weak upwelling during the summer months when the cyclonic along-shore winds temporarily relax. Hence, during the majority of the year the GOA is dominated by a downwelling circulation system.

There has been little research examining the distributions and concentrations of the major nutrients in this region prior to 1997. Therefore, the sources and distributions of the major nutrients in this region were not known. The nutrient data from this research, part of the Gulf of Alaska GLOBEC Long Term Observation Program (LTOP), represent the first systematic yearly record of major nutrient concentrations across the GOA shelf. These data provide an initial examination of the seasonal distributions and concentrations of nitrate, silicate, phosphate, and ammonium relative to the physical properties and phytoplankton biomass across the northern GOA shelf.

1.2 The general hydrography of the Gulf of Alaska

1.2.1 Gulf of Alaska Currents

The Gulf of Alaska is dominated by a large-scale cyclonic subarctic gyre (Fig. 1.1) (REED and SCHUMACHER, 1986). This counter-clockwise flow around the gulf induces horizontal divergence and upwelling at the center of the gyre (INGRAHAM JR. et al., 1976). This creates an upward flux of water from a southerly origin, with high salinity, low temperature, low dissolved oxygen, and high nutrient concentrations (FAVORITE et al., 1976). The gyre, as described by Reed and Schumacher (1987), consists of the North Pacific Current which flows eastward across the North Pacific in the vicinity of 45-50°N latitude, and then bifurcates into the Alaska Current and the California Current. The Alaska Current flows northward and then westward along the continental slope. The width of the Alaska Current varies from 400 km wide at the head of the gulf to less than 100 km wide west of Kodiak Island. West of ~150°W, the Alaska Current is considered the Alaskan Stream since the flow is high-speed narrow, boundary flow. The Alaskan Stream continues along the southern edge of the Aleutian Islands where the flow either turns north into the Bering Sea through Aleutian Island passes or south completing the Gulf of Alaska gyre (FAVORITE et al., 1976). The flow at the head of the gulf within the Alaska Current averages ~5 cm sec^{-1} and reaches peak speeds of approximately 30 cm sec^{-1}, whereas the flow within the Alaskan Stream averages around 20 cm sec^{-1} and reaches peak speeds of ~100 cm sec^{-1} (REED and SCHUMACHER, 1986).

There is a distinct flow along the coast of the GOA termed the Alaska Coastal Current (ACC) (Fig. 1.1). This flow has a strong seasonal signal with maximum speeds in the fall, September and October, when there is maximum precipitation and continental runoff (ROYER, 1982). The low salinity water induces baroclinic flow along the coast and produces a very stable water column. Throughout the year, the surface salinity of the coastal waters may change by up to seven parts per thousand. The surface temperatures also vary by about seven degrees Celsius, although this temperature range only induces a

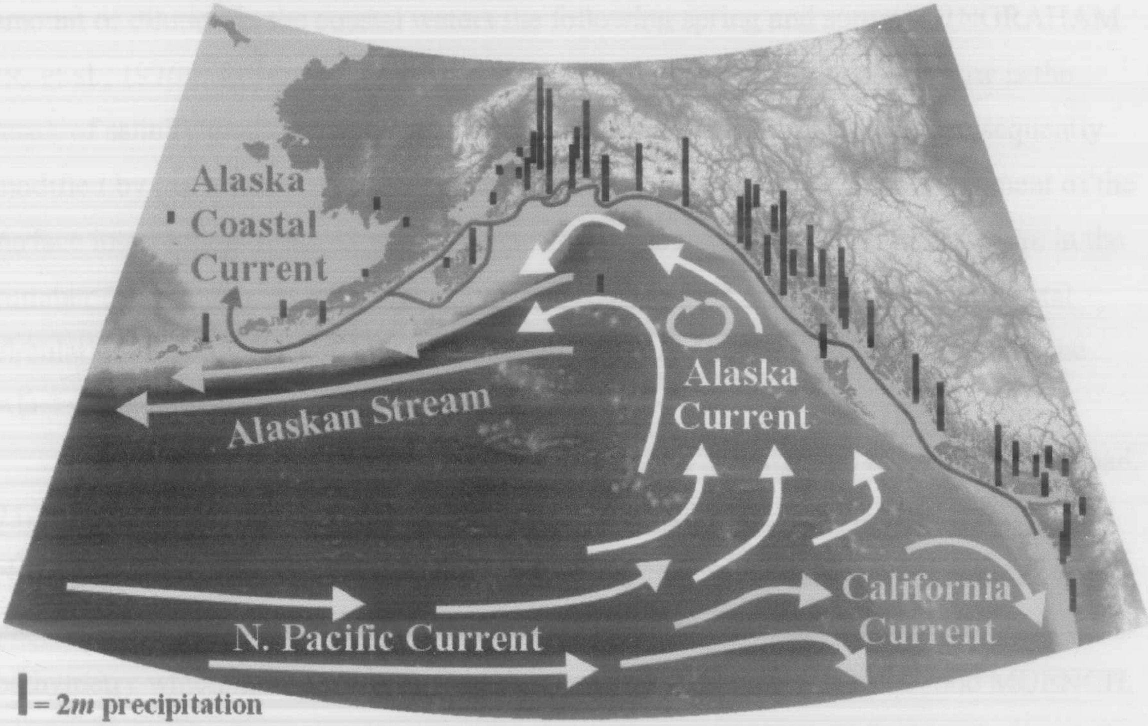

Fig. 1.1 Gulf of Alaska surface currents (arrows) and mean annual precipitation totals (black vertical bars).

shift of about one sigma-t unit in density (1 kg m^{-3}). On the other hand, the range in salinity affects density by four to five sigma-t units (kg m^{-3}) (REED and SCHUMACHER, 1986). Therefore, changes in salinity exert a much larger influence on the density distributions and baroclinic flow over the shelf (ROYER, 1981). The storage of precipitation as ice and snow along the GOA coast determines to a great extent the amount of dilution in the coastal waters the following spring and summer (INGRAHAM JR. et al., 1976). Royer (1982) concluded that the narrow, intense coastal flow is the result of salinity gradients that are controlled by freshwater discharge and subsequently modified by the winds. The coastal runoff produces a seasonal offshore movement of the surface intersection of the 32 psu isohaline which moves as far as 200 km offshore in the summer compared to its winter position (INGRAHAM JR. et al., 1976). The coastal circulation is also influenced by the locations and flows of the Alaska Current and the Alaskan Stream.

The flows on the GOA shelf are unusual in that they travel over a relatively broad, 75-150 km, and deep, 150-250 m, continental shelf (ROYER and MUENCH, 1977). Numerous silled and unsilled fjords, embayments, capes, and island groups complicate the coastline (REED and SCHUMACHER, 1986). The flows are influenced by complex bathymetry which includes numerous ridge and trough features (ROYER and MUENCH, 1977). There are also submarine canyons that influence the bottom flows and potentially provide conduits for the flow of deep, dense, nutrient-rich waters onto the shelf. For instance, Hinchinbrook Canyon, which leads into Prince William Sound, is believed to affect the chemical and biological dynamics within the sound.

There is mounting evidence of small, transient eddies that frequent the GOA shelf in addition to very large, long lasting eddies which travel along the continental slope for two to three years (CRAWFORD and WHITNEY, 1999). These eddies probably influence the physical properties, and consequently the chemical and biological properties over the shelf and slope. Recent observations of large, anticyclonic mesoscale eddies indicate that they are generated off the eastern coast of the GOA between Vancouver Island and Kayak Island. These eddies, which were larger during ENSO winters when the northward, along shore currents along the eastern GOA were stronger, transport shelf waters, which are fresher and higher in nutrients, to the middle-gulf. They have been observed in the northern GOA within our study region following the continental slope and the Aleutian Trench south of the Aleutian Islands. There is also evidence of smaller eddy activity in the coastal flow over the shelf. For example, eddies occur off the west side of Kayak Island, just east of the study area (REED and SCHUMACHER, 1986). Occasionally, density profiles across the Seward Line have depicted doming isopycnals indicating eddy-like activity over the shelf. These eddies, big and small, could influence the nutrient distributions by transporting and mixing the water column; therefore, they could play a potentially large role in supplying nutrients to the euphotic zone.

1.2.2 Atmospheric dynamics

An energetic winter season dominates the annual atmospheric cycle over the GOA. The Aleutian Low pressure system travels from the Bering Sea over the Alaska Peninsula into the GOA in August bringing with it maximum cyclonic winds which commence in November and continue through January (INGRAHAM JR. et al., 1976). This wind regime along the Gulf of Alaska coast generates downwelling which is most intense during the winter months (REED and SCHUMACHER, 1986). During these months, the along-shore winds induce maximum Ekman onshore transport at the surface and elevate the sea surface along the coast. These events cause downwelling which traps the relatively low salinity water against the coast (INGRAHAM JR. et al., 1976). Regional winds typically blow westward along the coastline throughout the year except for one or two months in the summer when the coastal zone experiences slight upwelling as the along-shore winds relax when the North Pacific High dominates (REED and SCHUMACHER, 1986). Therefore, the atmospheric circulation undergoes a strong annual cycle, which is reflected in the annual cycle of water properties and water circulation around the GOA and over the shelf.

The shelf water properties in this region have two extremes as described by Royer (1975). During winter, the intensification of cyclonic atmospheric circulation over the GOA produces easterly coastal winds and downwelling. The winds and thermohaline processes also contribute to vertical mixing of the water column such that shelf waters under winter conditions are vertically well-mixed with elevated salinities and low temperatures. During summer, stratification increases due to freshwater inputs and solar insulation as the coastal winds decrease allowing the downwelling to relax and create a weak upwelling response. The shelf waters under summer and fall conditions are stratified in temperature, salinity, and density with temperatures at their maximum and salinities at their minimum within the annual cycle.

On longer time scales, there is evidence of interannual variations in the GOA flows and properties resulting from the climatic variability of the El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Throughout the twentieth century, PDO events, or phases, persisted for 20 to 30 years while ENSO events persisted 6 to 18 months (MANTUA, 1999). Evidence of the PDO is most visible in the North Pacific with secondary signatures in the tropics, but the opposite is true for ENSO. It has recently been discovered that 'warm' phases of the PDO enhance coastal ocean biological productivity in various Alaskan waters while inhibiting productivity off the west coast of the United States, while 'cool' phases have the opposite pattern. It appears that the most recent 'warm' phase of the PDO lasted from 1977 through 1999 and has since entered into a 'cool' phase (NASA, 2000). There was also a strong El Nino in 1997-1998 (NOAA, 2001). These phase changes of ENSO and PDO encompass the years this data was collected and could potentially account for interannual variability found in the oceanographic properties of the northern GOA.

2. METHODS

2.1 Collection methods

The data discussed here were collected from twelve cruises in 1998 and 1999 aboard the R.V. *Alpha Helix* as part of the Global Ocean Ecosystem Dynamics (GLOBEC) Gulf of Alaska Long Time Series Observation Program (LTOP). The cruises took place in March, April, May, July-August, October, and December. Several transects were occupied during each cruise in an order of priority in which the Seward Line, the focus of this paper, was foremost (Table 2.1). The Seward Line is a cross-shelf transect which encompasses both the shelf waters within the Alaska Coastal Current and the slope waters within the Alaskan Stream (Fig. 2.1). This transect and these occupations allowed for preliminary observations of the seasonal cycles and interannual variability of the chemical, physical, and biological properties across the northern GOA shelf.

Table 2.1 Seward Line occupations throughout 1998 and 1999.

1998	1999
8-13 March	15-18 March
1-5 April	12-15 April
7-12 May	6-9 May
10-13 July	27-29 August
3-8 October	5-9 October
2-4 December	2-4 December

Nutrient samples were collected at stations along the Seward Line transect with a Sea Bird 911 Plus CTD/rosette sampler with twelve five liter Niskin bottles. Samples were taken every 10 m in the upper 50 m. Samples below 50 m were taken at varying intervals throughout the water column, depending on station depth and variations in the

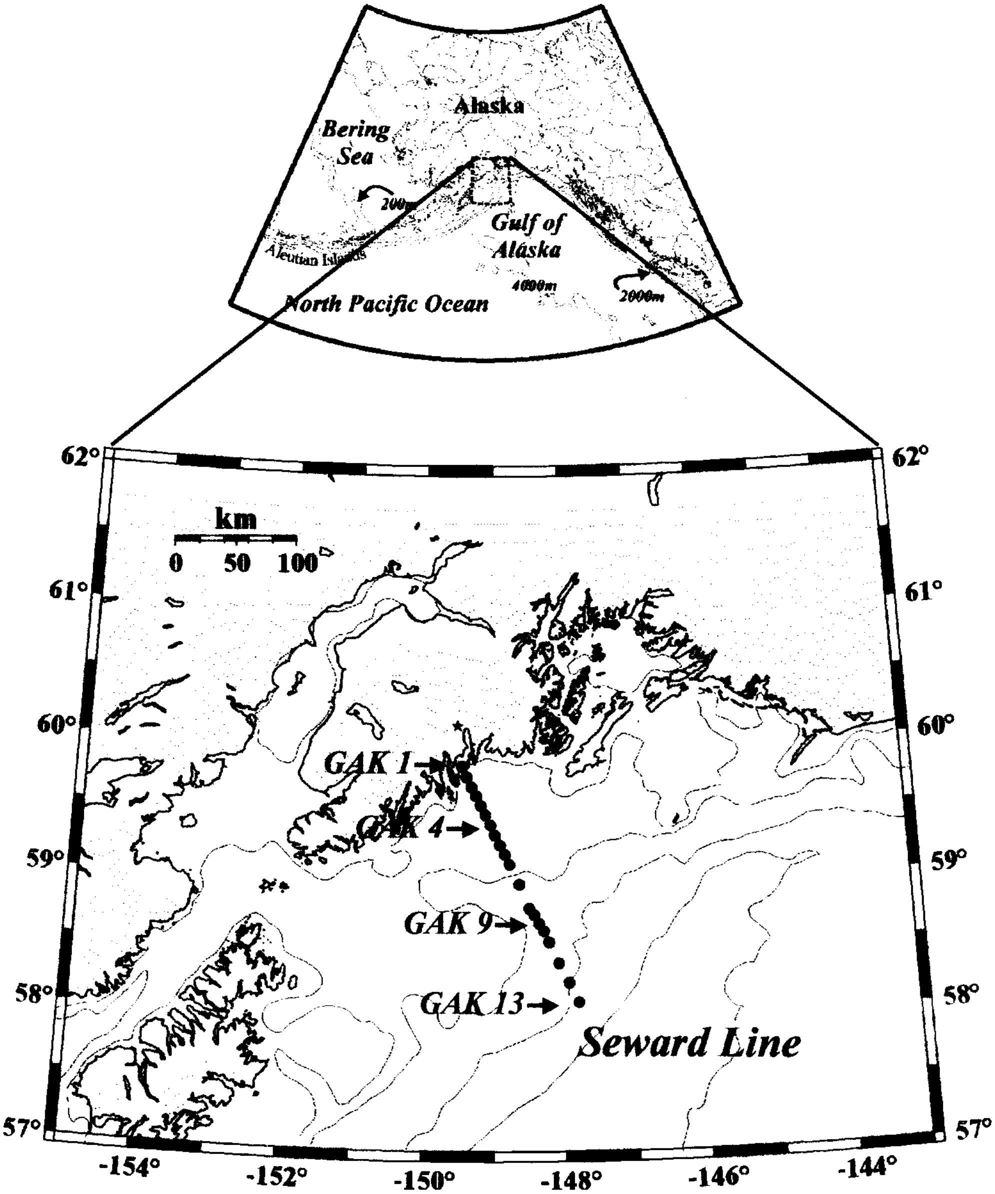

Fig. 2.1 The Gulf of Alaska GLOBEC Seward Line with labeled stations: GAK 1, GAK 4, GAK 9, and GAK 13.

temperature, salinity, or fluorescence profiles. Samples collected in 1998 were frozen for later analysis of nitrate, nitrite, silicate, phosphate, and ammonium in the laboratory. Samples collected in 1999 were analyzed aboard ship for nitrate, nitrite, silicate, phosphate, and ammonium shortly after sampling. The samples were collected in association with temperature and conductivity measurements taken by a CTD/rosette system. A Wet Labs fluorometer attached to the CTD/rosette system provided chlorophyll fluorescence profiles at each station. Discrete upper water column samples were also collected for *in vitro* chlorophyll analysis.

2.2 Chemical analyses

The chemical analyses of nitrate, nitrite, silicate, phosphate, and ammonium were performed using the colorimetric techniques on Technicon AutoAnalyzer II and Alpkem model 300 continuous nutrient analyzers (WHITLEDGE et al., 1981). These instruments allow for rapid analysis of up to six parameters on a large number of samples. Water samples collected in polyethylene scintillation vials were pumped into a manifold where the appropriate chemicals were added and mixed to produce an observable color which was measured in a colorimeter.

2.2.1 Nitrate and nitrite

Nitrite, NO_2^-, concentrations were determined by the Greiss reaction in which sulfanilimide, dissolved in diluted hydrochloric acid, was first added to the water sample as the diazotizing agent. N-(1-Naphthyl) ethylenediamine dihydrochloride (NNED) was then added as the coupling reagent which reacted with NO_2^- to produce an extremely pink diazo dye with an absorption maximum at 540 nm (BENDSCHNEIDER and ROBINSON, 1952).

Nitrate, NO_3^-, concentrations were also determined using the Greiss reaction. However, this nutrient analysis requires an additional step. The NO_3^- within the water samples was first reduced to NO_2^- as it passed through a cadmium-copper reduction coil

(WOOD et al., 1967). An imidazole buffer was added before the cadmium column to eliminate any interference due to iron, copper, or other metals (ALPKEM CORPORATION, 1986). In addition, nitrogen gas was supplied to this channel as the segmentation gas, as it helps maintain a constant pH by minimizing the formation of cadmium hydroxide from the reaction of oxygen on the reactor wall (ALPKEM CORPORATION, 1986). Sulfanilimide and NNED were then added to the samples, which reacted with NO_2^- to form the pink diazo dye measured in the colorimeter (WOOD et al., 1967; WHITLEDGE et al., 1981). Consequently, this channel measured both NO_3^- and NO_2^-; therefore, the NO_2^- concentration was subtracted from the $NO_3^- + NO_2^-$ concentration for each sample to determine NO_3^- concentrations.

2.2.2 Silicate

Orthosilicic acid, $Si(OH)_4$, or reactive silicate, $(SiO_2)_n$ + water, (where n = 1, 2, 3, 4) concentrations were determined by a set of three reactions. The first reaction involved ammonium molybdate, dissolved in a dilute sulfuric acid solution, which transformed $Si(OH)_4$ into silicomolybdic acid (ARMSTRONG et al., 1967). Tartaric acid was added to prevent interference by phosphomolybdate and arsenomolybdate, which may have formed in the previous reaction, by dissolving these complexes (MULLIN and RILEY, 1955). The silicomolybdic acid was then reduced by the addition of stannous chloride to molybdenum blue, which has an absorption maximum of 820 nm (WHITLEDGE et al., 1981).

2.2.3 Phosphate

Orthophosphate is present in various ionic forms in seawater: $H_2PO_4^-$, HPO_4^{-2}, or PO_4^{-3}. These concentrations were determined by treating the samples with an ammonium molybdate/potassium antimonyl tartrate (KAT) solution and ascorbic acid. This solution reacts with phosphate by reducing the phosphate ions into phosphomolybdic acid, which contains antimony and phosphate in a 1:1 atomic ratio. The samples were heated to 30°C to accelerate the reaction. This new complex, called phosphomolybdem blue, is a blue-purple color with an absorption maximum of 880 nm (MURPHY and RILEY, 1962).

2.2.4 Ammonium

Ammonium, NH_4^+, concentrations were determined by the Berthelot reaction (SLAWYK and MACISAAC, 1972). As the water samples passed through the manifold a dilution complex was added which consisted of sodium citrate and sodium hydroxide (PATTON and CROUCH, 1977). This buffer solution maintained a basic pH which ensured both rapid formation and minimal decomposition of the first intermediate (PATTON and CROUCH, 1977). Next, reagent A was added, which was a solution of phenol and sodium nitroprusside (SLAWYK and MACISAAC, 1972). The sodium nitroprusside acted as a catalyst as it increased the sensitivity and rate of the reaction (PATTON and CROUCH, 1977). Reagent B was then added, which was a basic solution of hypochlorous acid (Chlorox) and sodium hydroxide. Finally, the samples were heated to 60°C. Altogether, the hypochlorous acid and phenol reacted with NH_4^+ in an aqueous alkaline solution of sodium citrate and sodium hydroxide to produce indophenol blue (WHITLEDGE et al., 1981). The indophenol blue is an intensely blue chromophore with an absorption maximum at 637 nm (WHITLEDGE et al., 1981). This procedure is a modification of the Slawyk and MacIsaac (1972) procedure.

2.2.5 Chemical preparation

The chemical solutions and standards were prepared with deionized water (DIW) treated by a Millipore ultrapure water system. All the chemical solutions and stock standard solutions were stored in a refrigerator except those that should not be refrigerated. Nutrient standards were prepared daily from stock standard solutions that were prepared approximately twice a year. Nitrate and silicate were prepared together as a set of standards, S-1's, with the following concentrations: 5.0, 15.0, 25.0, 35.0, and 45.0 μmole l^{-1}. Nitrite, phosphate, and ammonium standards were prepared as another set of standards, S-2's, with the following concentrations: 0.5, 1.5, 2.5, 3.5, and 4.5 μmole l^{-1}. A sync was also prepared daily, which included all five nutrients at the highest concentration or twice the highest concentration to check that the chemical channels were separating the nutrients accordingly and working properly. The standard and sample peaks were recorded on strip charts to an accuracy of $\pm$0.01 volts with a full-scale range of five volts. The two sets of five standards, plus the occasional sync, were run routinely between sample runs. The standards provided a series of absorption peaks for each known nutrient concentration, which created a slope, which was then used to calculate the seawater sample concentrations.

During 1999, when the samples were analyzed onboard, standards from each set were run systematically at the beginning of the sample runs to survey the accuracy and reproducibility of the Technicon AutoAnalyzer II. These standards were used to calculate the percent error, standard deviation, and 95% confidence intervals for each channel averaged over each cruise and over the year (Table 2.2). The yearly average percent error for all five channels was between 4% and 10%, with the nitrate, silicate, and nitrate + nitrite channels being the most accurate and the ammonium and phosphate channels slightly less accurate. The yearly averaged 95% confidence interval produced ranges of $\pm$0.09 µmole l^{-1} NO_2^-, $\pm$0.19 µmole l^{-1} NH_4^+, $\pm$0.25 µmole l^{-1} PO_4^{-3}, $\pm$0.78 µmole l^{-1} $NO_2^- + NO_3^-$, and $\pm$1.35 µmole l^{-1} $Si(OH)_4$. Duplicates were also ran occasionally on seawater samples, which presented similar high levels of reproducibility.

2.2.6 Chlorophyll a

Chlorophyll *a* concentrations were determined using an acetone/DMSO extraction procedure measured on a Turner Designs model 10AU fluorometer (SHOAF and LIUM, 1976). Onboard, a known amount of seawater, commonly 1.0 liter, was filtered through a 25 or 47 cm GF/F glass microfibre filter with a nominal pore size of 0.7 µm. The filters were then stored in a freezer in labeled aluminum foil envelopes. Onshore, the pigments were extracted from the filters by submerging the filters in an acetone/DMSO solution overnight in a freezer (SHOAF and LIUM, 1976). The samples were then brought to room temperature, mixed vigorously, and read in a fluorometer to determine chlorophyll

Table 2.2 Nutrient standard concentrations and measured concentrations with one standard deviation and the number of replicates averaged over each cruise in 1999. Yearly mean of percent error and 95% confidence intervals for each nutrient channel.

1999	PO_4			$Si(OH)_4$			N+N			NO_2			NH_4		
	Std.	**Meas.**	**#**	**Std.**	**Meas.**	**#**	**Std.**	**Meas.**	**#**	**Std.**	**Meas.**	**#**	**Std.**	**Meas.**	**#**
March	4.50	3.90 ± 0.41	2	45.00	47.17 ± 2.11	6	4.50	4.47 ± 0.21	6	4.50	4.45 ± 0.05	6	4.50	4.32 ± 0.23	5
April	4.50	4.30 ± 0.27	19	45.00	45.50 ± 1.76	29	45.00	45.36 ± 0.67	29	4.50	4.46 ± 0.13	28	4.50	4.26 ± 0.43	27
	2.50	2.57 ± 0.21	15	25.00	26.87 ± 2.56	15	25.00	25.82 ± 0.97	15	2.50	2.53 ± 0.07	15	2.50	2.41 ± 0.21	15
May	4.50	4.33 ± 0.23	16	45.00	44.86 ± 1.92	30	45.00	44.89 ± 1.33	30	4.50	4.39 ± 0.09	26	4.50	4.32 ± 0.42	26
August	2.50	2.47 ± 0.58	15	45.00	44.83 ± 1.66	11	45.00	44.68 ± 3.45	12	2.50	2.53 ± 0.10	14	2.50	2.20 ± 0.30	14
October	2.50	2.48 ± 0.40	7	45.00	47.36 ± 2.76	5	45.00	40.82 ± 1.33	5	2.50	2.46 ± 0.12	8	2.50	2.47 ± 0.24	8
December	2.50	2.68 ± 0.42	9	25.00	26.41 ± 2.61	9	25.00	24.74 ± 1.50	9	2.50	2.60 ± 0.42	7	2.50	2.57 ± 0.58	9
% Error	**10%**			**5%**			**6%**			**4%**			**8%**		
95% Conf. Int.	**0.25**			**1.35**			**0.78**			**0.09**			**0.19**		

a concentrations (a modification of (PARSONS et al., 1984). Fluorometers were calibrated with commercial standards over a range of 0.1 to 150 μg chl *a* l^{-1}.

2.2.6 Contouring

The temperature, salinity, and nutrient concentrations were contoured for each cruise across the Seward Line using the contouring program, Ocean Data View (ODV). These contour plots display the discrete sample depths with dots and the CTD data taken in one meter intervals in vertical black lines. Time series contour plots at individual stations were also generated with ODV, and likewise display the dots and vertical lines showing sampling locations.

3. RESULTS

3.1 The annual cycle of nutrient concentrations across the Seward Line

The cross-shelf nutrient distributions over an annual cycle were measured along the Seward Line transect. Nitrate, silicate, and phosphate demonstrated general annual patterns in response to phytoplankton activity and the local physical characteristics. Ammonium distributions during this time were mostly related to other biological activities. During the winter season, incident solar radiation was low, the water column was well-mixed, and the phytoplankton biomass was low. Consequently, the nutrients in the upper water column were at their maximum concentrations. The spring bloom of phytoplankton partially depleted nutrient concentrations. In the upper 30-40 m of the water column, concentrations of nitrate, silicate, and phosphate were greatly reduced by late summer and fall as a result of continuous drawdown by phytoplankton throughout the summer. As winter mixing resumed and the phytoplankton biomass diminished, the surface waters were replenished. Both 1998 and 1999 showed this annual cycle of increasing and decreasing surface nutrient concentrations.

At depth, both years exhibited an onshore flux of dense nutrient-rich waters onto the shelf during the summer months when the downwelling winds relaxed. This created a nutrient enriched bottom layer over the inner shelf that was subsequently mixed throughout the water column by winter storm events. Although magnitudes varied, the annual cycles from 1998 and 1999 were similar and, therefore, only the 1999 annual cycle will be discussed. Notable interannual differences between 1998 and 1999, however, are discussed in section 3.2.

The Seward Line can be characterized as having four regimes as defined by water mass structure and circulation characteristics (WEINGARTNER, personal communication) (Fig. 3.1). The inner shelf regime consists of the region of the shelf within the Alaska Coastal Current which varies in width, but is generally within ~50 km of the coast. The middle shelf regime is the domain between the inner shelf and shelf-

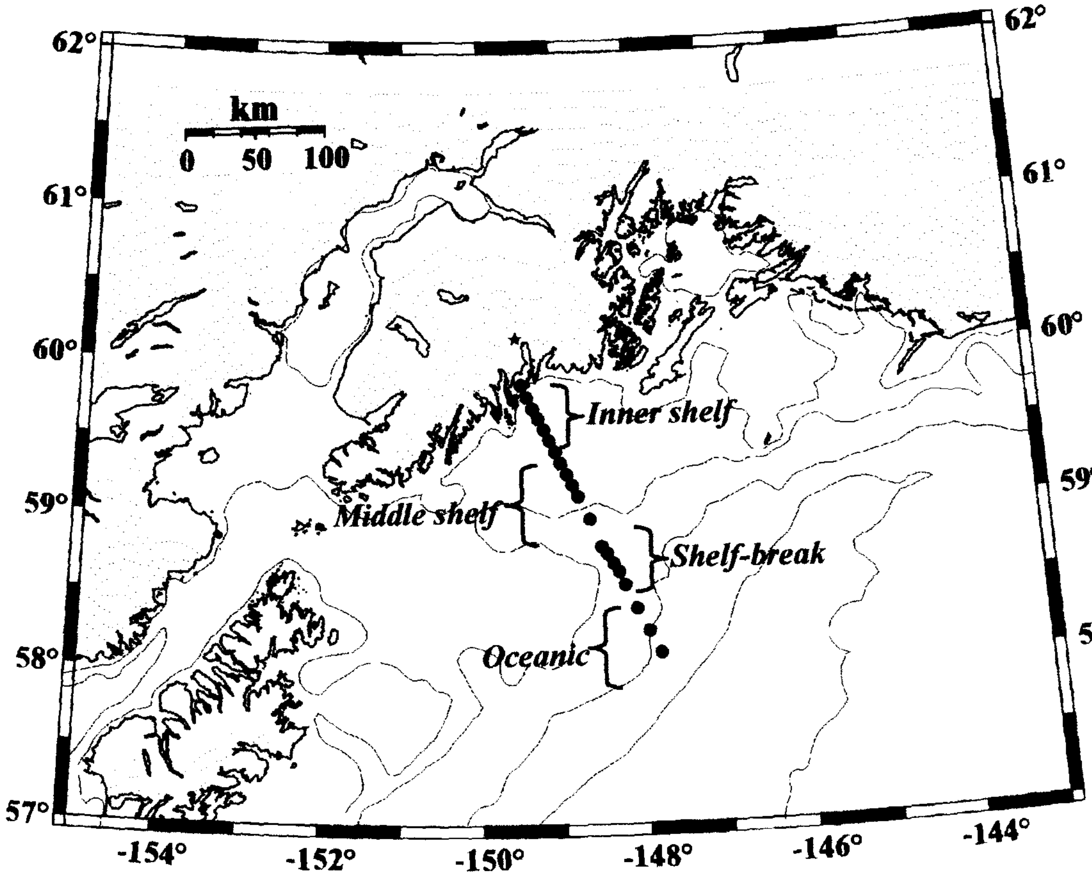

Fig. 3.1 Seward Line separated into four shelf regimes: inner shelf regime, middle shelf regime, shelf-break regime, and oceanic or offshore regime.

break, ~50-125 km from the coast. This domain is characterized by relatively weak flow influenced by mesoscale variability. The outer shelf or shelf-break regime involves the region of the shelf dominated by the shelf-break front, 135-160 km from the coast. The off shelf or oceanic regime includes the region offshore of the shelf-break regime over the continental slope, typically within the Alaskan Stream.

3.1.1 Spring 1999: Temperature, salinity, nitrate, and chlorophyll a distributions

In March and April 1999, at the end of winter, the upper 100 m of the water column across the transect was well mixed with temperatures between 3.5 and 5.3 °C and salinities between 31.7 psu inshore and 33.4 psu offshore (Fig. 3.2, 3.3). In general, nitrate concentrations increased with depth and distance offshore in March and April. The surface nitrate concentrations across the transect were 12-18 μmole l^{-1} in the upper 50 m and increased with depth to > 25 μmole l^{-1} below 200 m offshore of the shelf-break, 150-250 km offshore (Fig. 3.2, 3.3). The maximum nitrate concentrations were offshore of the shelf-break below the permanent halocline (200-250 m, 32.5 to 33.8 psu), with values as high as 45 μmole l^{-1} NO_3^-. Nitrate concentrations integrated over the upper 50 m in all shelf regimes were higher in early spring than in the other seasons throughout the year (Fig. 3.4). (The integrated nutrient concentrations discussed and presented throughout this thesis were all calculated by integrating data from the upper 50 m.)

In early spring, the inner shelf was well mixed with the lowest temperatures and lowest salinities occurring along the coastline, within the ACC (Fig. 3.2). Warmer temperatures and higher salinities were seen at depth in the outer shelf and offshore regimes. Within the upper water column, in March 1999 the lowest nitrate concentrations were in the upper 75-100 m of the inner shelf and oceanic regimes. There was a slight reduction (~2 μmole l^{-1}) in the upper water column nitrate concentrations over the inner shelf regime in April.

March fluorescence profiles and *in vitro* chlorophyll *a* concentrations showed low phytoplankton biomass, with surface chlorophyll *a* concentrations averaging 0.02 μg l^{-1} across the transect (Fig. 3.5). By April, chlorophyll *a* increased slightly with surface

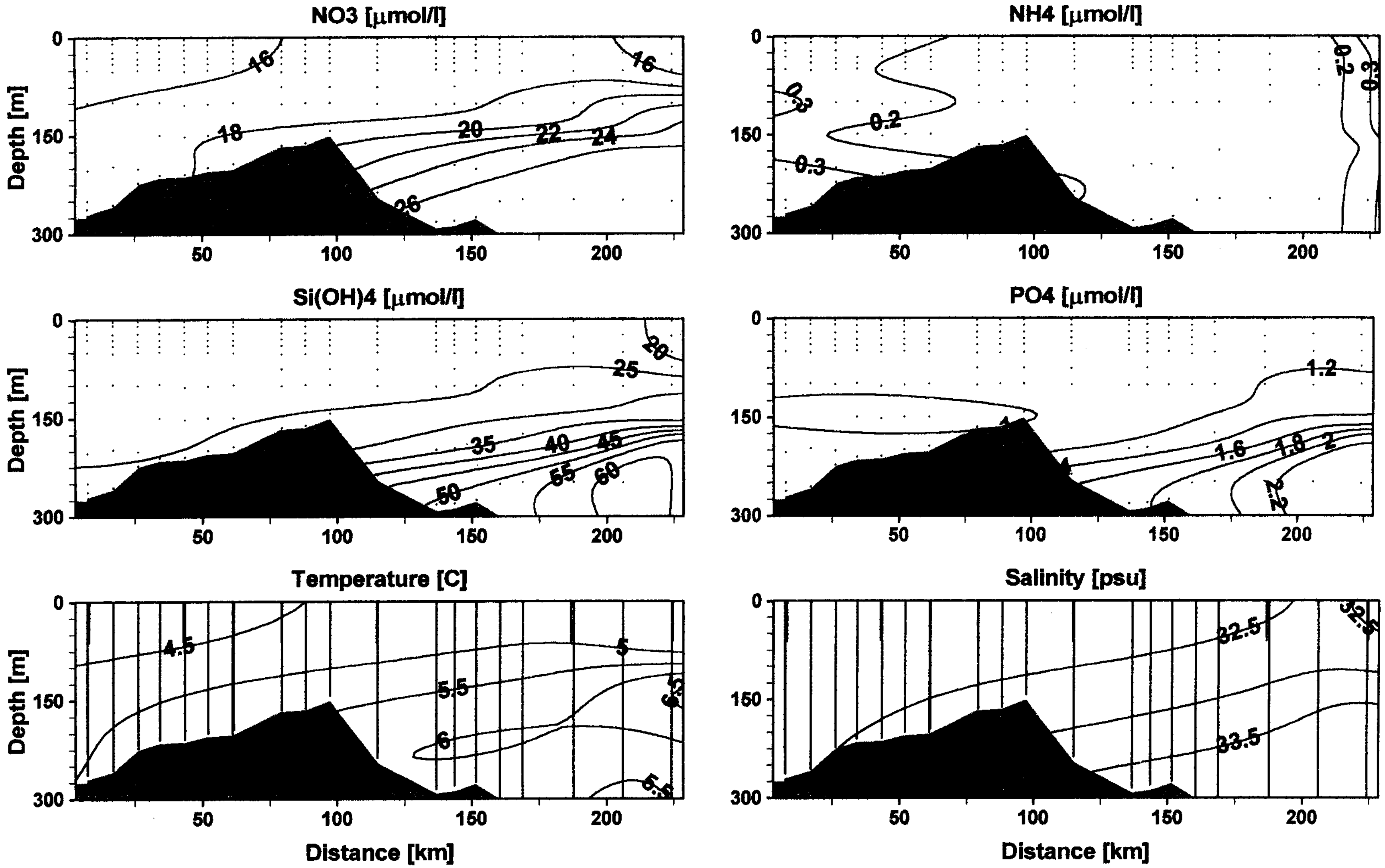

Fig. 3.2 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 15-18 March 1999. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).

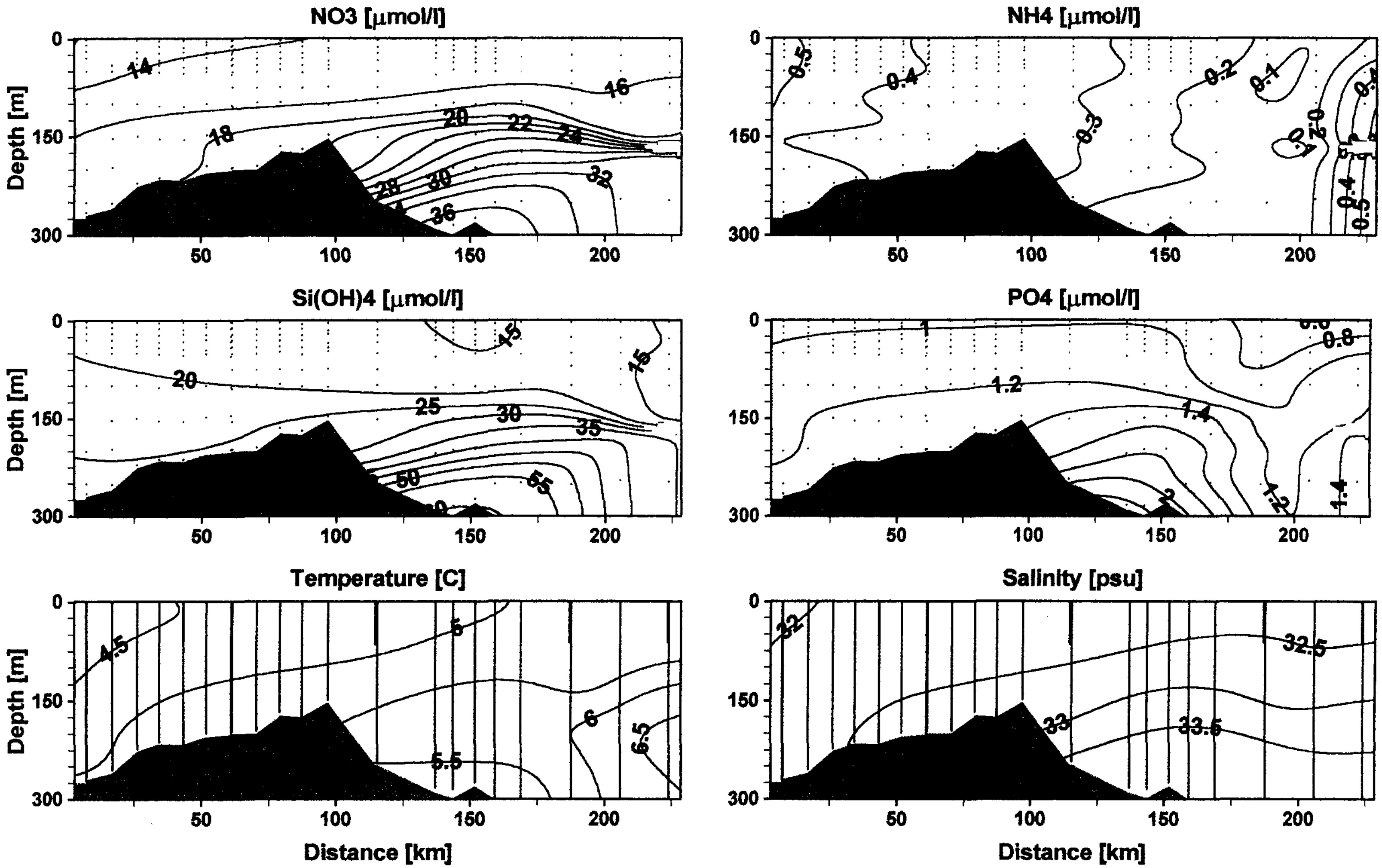

Fig. 3.3 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 12-15 April 1999. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).

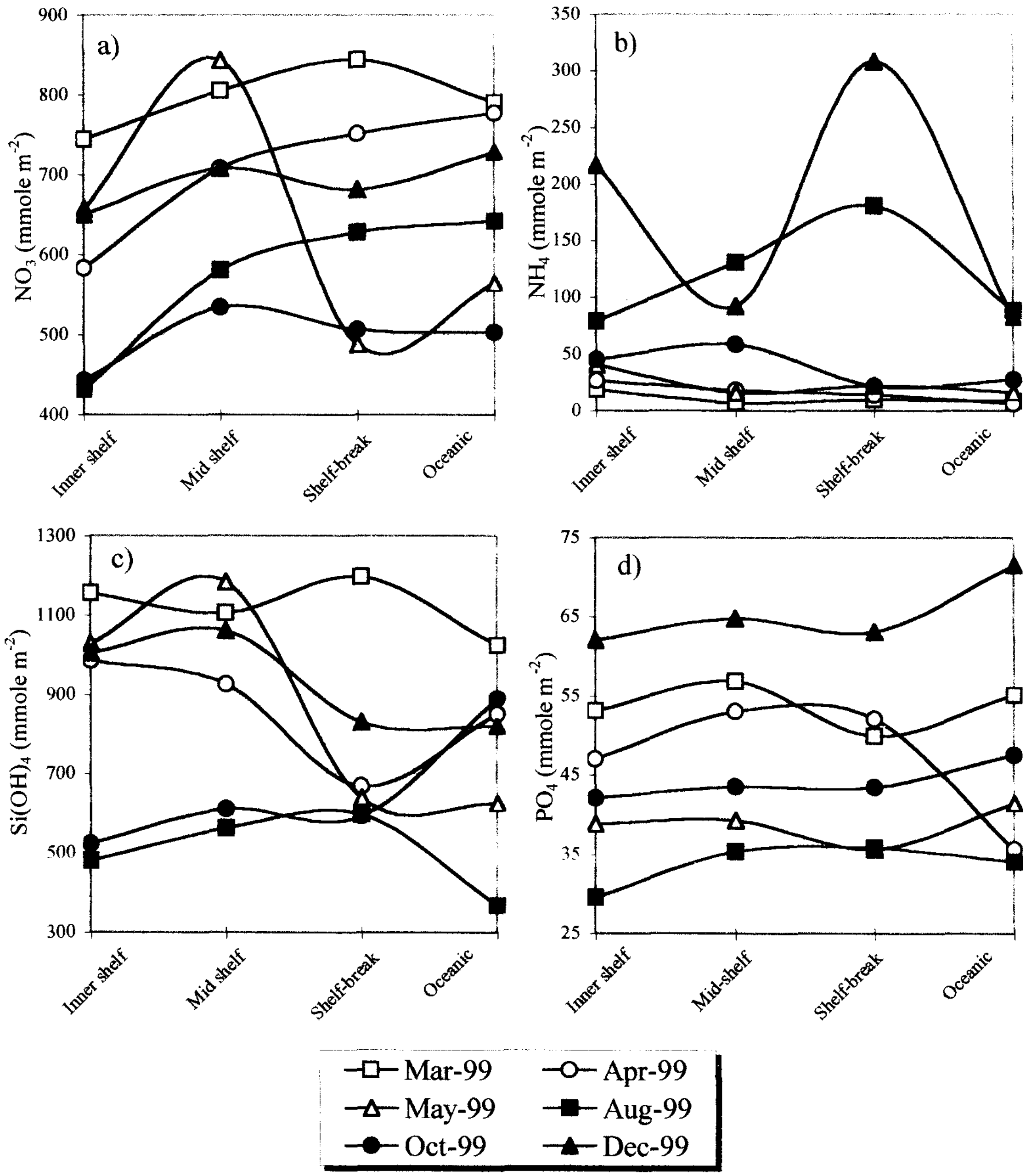

Fig. 3.4 Mean integrated (0-50 m) a) nitrate, b) ammonium, c) silicate, and d) phosphate concentrations across the Seward Line within the four shelf regimes, March through December 1999. Concentrations in mmole m^{-2}.

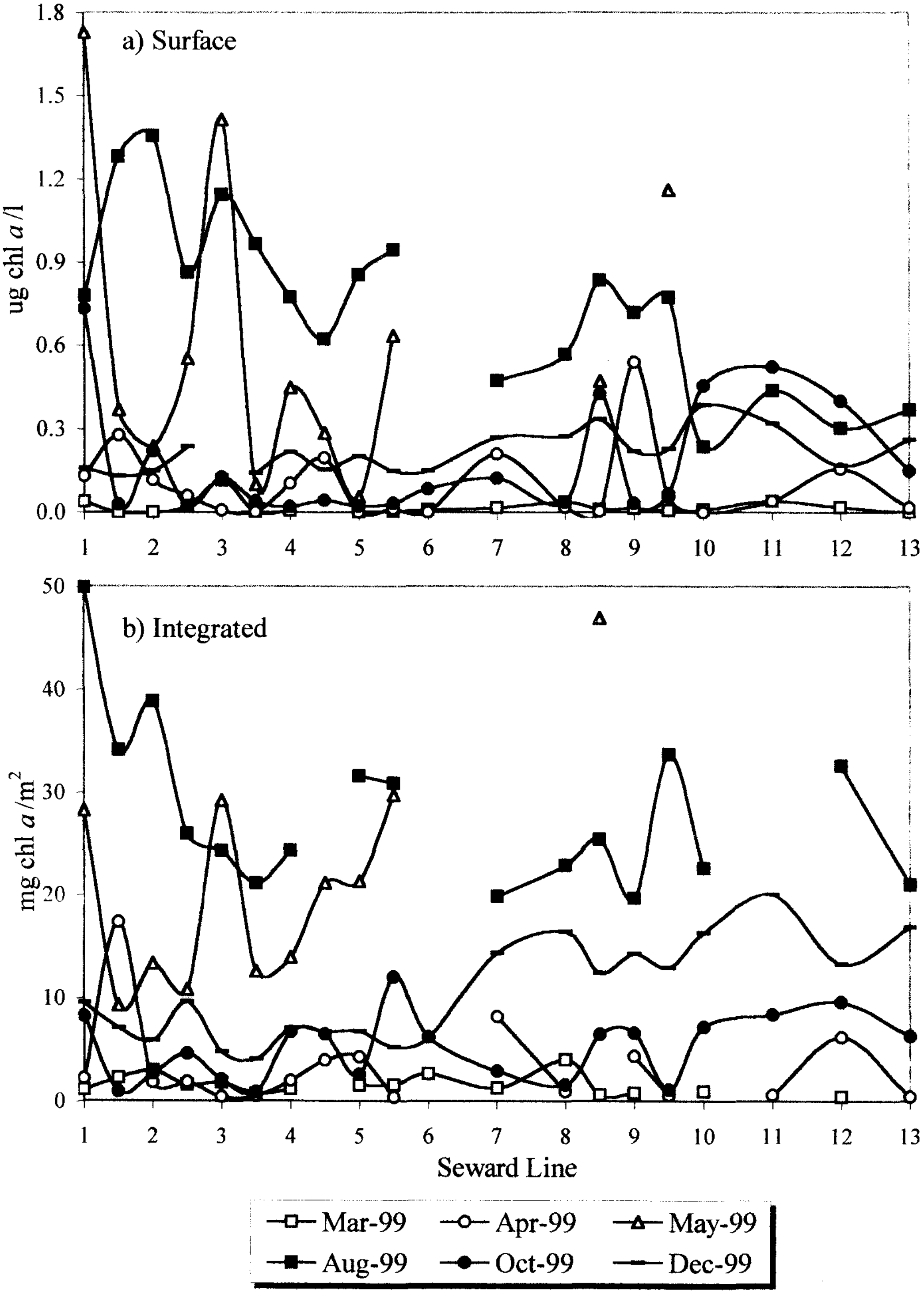

Fig. 3.5 Surface (a) and integrated (surface to 30-50 m) (b) chlorophyll *a* concentrations across the Seward Line, March through December 1999. Units are μg chl *a* l^{-1} and mg chl *a* m^{-2}.

concentrations averaging 0.10 μg l^{-1} across the shelf, with higher concentrations over the inner shelf and shelf-break. March integrated chlorophyll *a* (surface to 30-50 m) indicated uniformly low biomass across the shelf, with a mean concentration of 2.36 mg m^{-2}. April showed only minor increases at three of the stations (Fig. 3.5). (Integrated chlorophyll *a* concentrations discussed and presented here were calculated by integrating the upper 30-50 m, depending on the available data.)

In May 1999, the water column began to warm and stratify, with surface temperatures between 4.8 and 6.5°C and the lowest salinities along the coast (Fig. 3.6). Low nitrate concentrations were measured in the surface waters over the inner shelf and especially over the outer shelf and oceanic regimes, with nitrate concentrations as low as 1.0 μmole l^{-1}. However, over the middle shelf region, depth integrated nitrate had annually high surface nitrate concentrations (Fig 3.4).

In May, bottom waters below ~100 m were enriched in nitrate across the shelf, with concentrations higher than those measured in March and April. The larger nitrate concentrations extended over the shelf-break and rose closer to the surface offshore. The physical profiles displayed doming isohalines and isotherms, indicating possible cyclonic eddy activity over the shelf.

The fluorescence profiles and chlorophyll *a* concentrations from May 1999 showed a notable increase in phytoplankton biomass across the transect with surface chlorophyll *a* concentrations between 0.10 and 1.70 μg l^{-1} (Fig. 3.5). The surface chlorophyll *a* distributions across the transect were variable with higher values over the inner shelf and over the shelf-break. There was also an increase in phytoplankton biomass in the subsurface waters with a mean depth integrated concentration of 21.51 mg chl *a* m^{-2} (Fig. 3.5).

3.1.2 Summer1999: Temperature, salinity, nitrate, and chlorophyll a distributions

By late August, the water column was strongly stratified (Fig. 3.7). The surface waters across the transect reached temperatures between 12 and 14°C. The surface salinities were low over the inner and middle shelf, with salinities as low as 24.0 psu

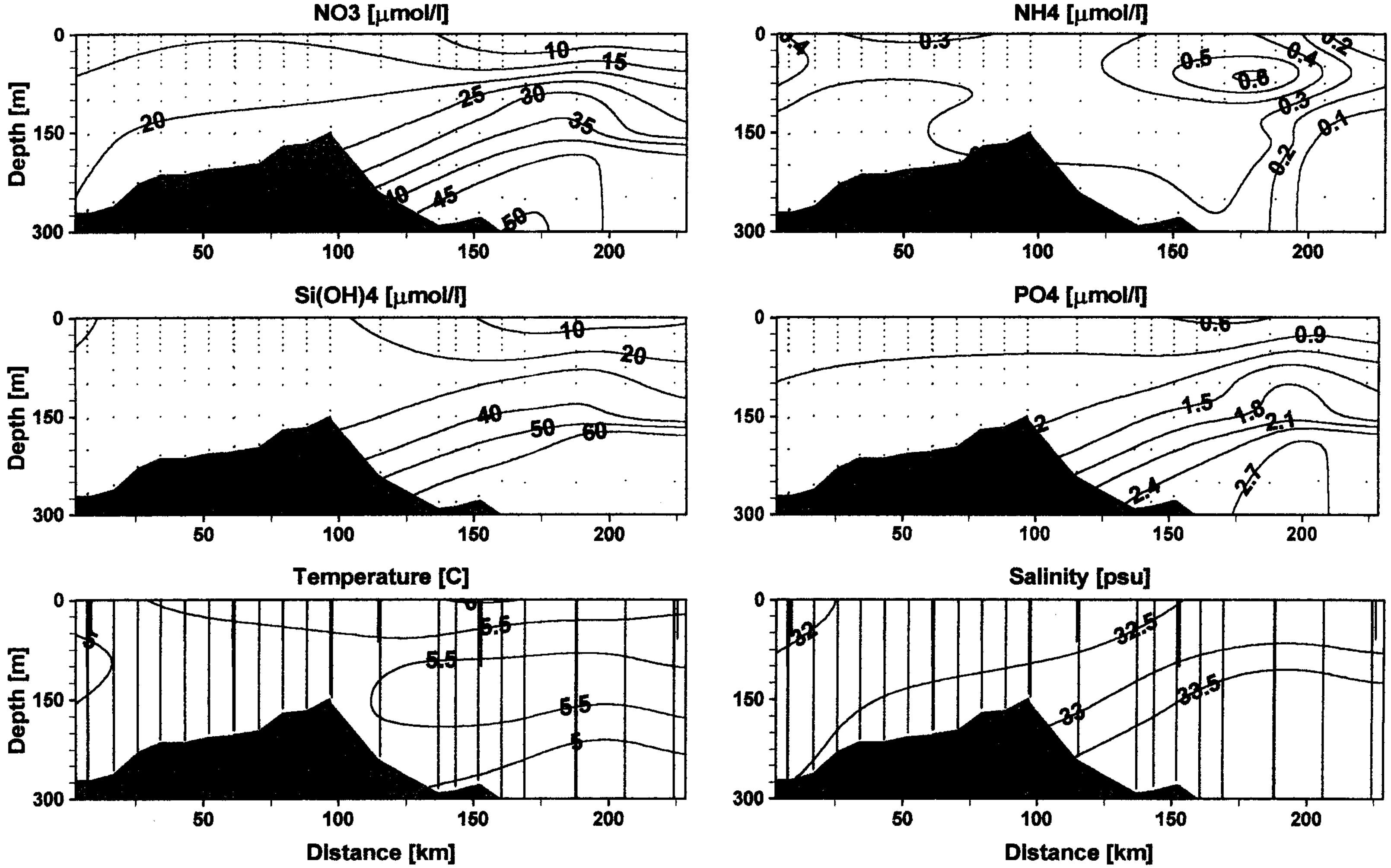

Fig. 3.6 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 6-9 May 1999. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).

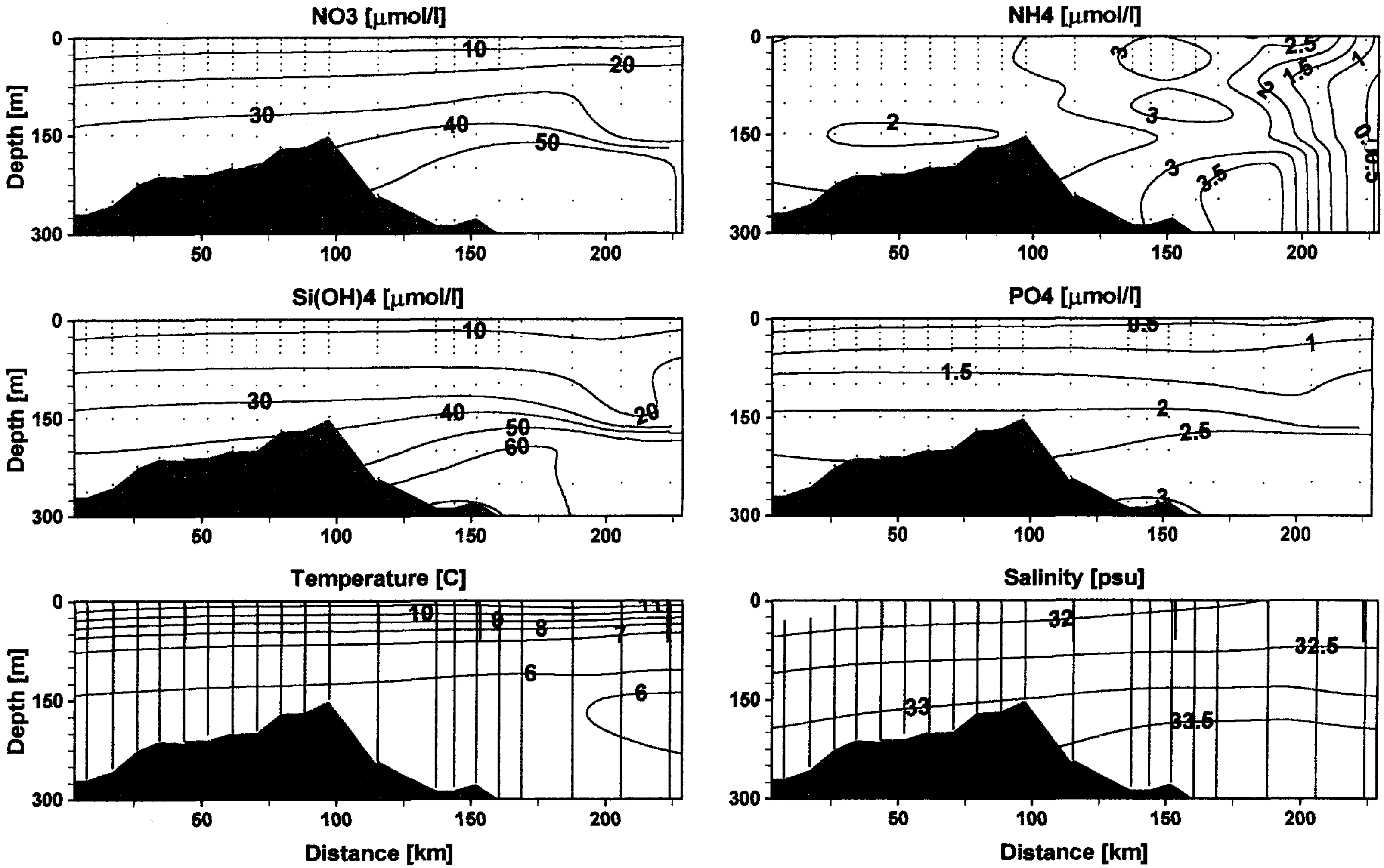

Fig. 3.7 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 27-29 August 1999. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).

along the coast. At this time, surface waters (< 10 m) across the shelf reached minimum nitrate concentrations, < 1.0 μmole l^{-1}. Nutrient depletion is commonly recognized to occur as concentrations become less than twice the half-saturation constant (K_S), which is equal to the nutrient concentration at half the maximum growth rate (μ_{max}). For nitrate, the range in K_S for phytoplankton in eutrophic oceanic waters is 0.5-2.0 μmole l^{-1} (LALLI and PARSONS, 1993). By this definition, the surface waters across the transect were nitrate depleted, and possibly nitrate limited, during late summer. Similarly, depth integrated nitrate concentrations were low across the shelf, especially over the inner shelf where integrated nitrate concentrations attained their annual minimum (Fig. 3.4).

Bottom shelf waters and waters offshore of the shelf-break were enriched in nitrate compared to those measured in May. The bottom waters below ~150 m over the inner and middle shelf contained nitrate concentrations > 28 μmole l^{-1} and the bottom waters below ~100 m over the shelf-break and further offshore contained nitrate concentrations > 30 μmole l^{-1} and reached concentrations as high as 49 μmole l^{-1}. These high concentrations were due to the seasonal onshore flux of deep offshore waters. Throughout the summer, the downwelling winds relaxed and the freshwater inputs from meltwater discharge and precipitation increased. Simultaneously along-shore winds relax and/or reverse, thereby allowing low salinity coastal waters to move offshore along the surface and deep waters to migrate onshore at depth (ROYER, personal communication). This onshore flux of dense, nitrate-rich water onto the shelf essentially creates a nitrate reservoir over the deeper portions of the inner shelf.

The August fluorescence profiles and chlorophyll *a* concentrations had relatively high phytoplankton biomass across the transect with a mean surface chlorophyll concentrations of 0.75 μg l^{-1} (Fig. 3.5). The highest surface chlorophyll *a* concentrations were measured over the inner shelf and decreased seaward across the transect with the lowest surface concentrations within the oceanic regime. Depth integrated chlorophyll *a* concentrations were also high, with concentrations as high as 49.95 mg m^{-2} near the coast and a mean of 27.83 mg m^{-2} (Fig. 3.5). The sub-surface layer was a region of higher stability due to thermal and freshwater stratification (Fig. 3.7).

3.1.3 Fall and early winter 1999: Temperature, salinity, nitrate, and chlorophyll a distributions

The data collected in October provided a glimpse of the nutrient concentrations at the end of a season of intense biological activity and as the physical regime responded to annually high freshwater inputs from precipitation and terrestrial inputs. The water column was stable and the relatively warm surface waters, (9-10°C) extended deeper into the water column than during summer (Fig. 3.8). The surface salinities across the transect were lowest, ~25.6 psu, near the coast within the ACC. Surface nitrate concentrations were similar to August. However, the low concentrations were now deeper in the water column, extending to 50-60 m. The surface waters across the transect remained low in nitrate, with concentrations ranging between 1.5-12.0 μmole l^{-1} in the upper 30 m. October had the annual minimum depth integrated nitrate concentrations across the shelf (Fig. 3.4). At depth, the reservoir of dense, nitrate-rich water measured over the inner shelf in August was now depleted in October. A decrease in nitrate concentrations offshore of the shelf-break was also measured.

The October fluorescence profiles and *in vitro* chlorophyll *a* data showed a large decrease in phytoplankton biomass across the transect compared to August (Fig. 3.5). Surface chlorophyll *a* concentrations averaged 0.18 μg l^{-1} in October, with higher biomass values near the coast, over the outer shelf, and within the oceanic regime. Depth integrated concentrations also decreased to a mean of 5.11 mg chl *a* m^{-2} (Fig. 3.5)

December conditions reflected onshore wind-mixing and decreasing freshwater inputs (Fig. 3.9). Compared to October, the stratification was weaker and surface salinities increased slightly from the October conditions. Lowest salinities, ~30.0 psu, remained along the coast within the ACC. The warmest water temperatures extended throughout the water column over the inner shelf. The depth integrated nitrate rebounded from the low concentrations in October and approached concentrations measured in April (Fig. 3.4). The surface nitrate concentrations ranged from 9.0 to 17.0 μmole l^{-1} in the upper 50 m, with the lowest concentrations within the ACC.

The flux of nitrate into the upper water column from the bottom waters over the

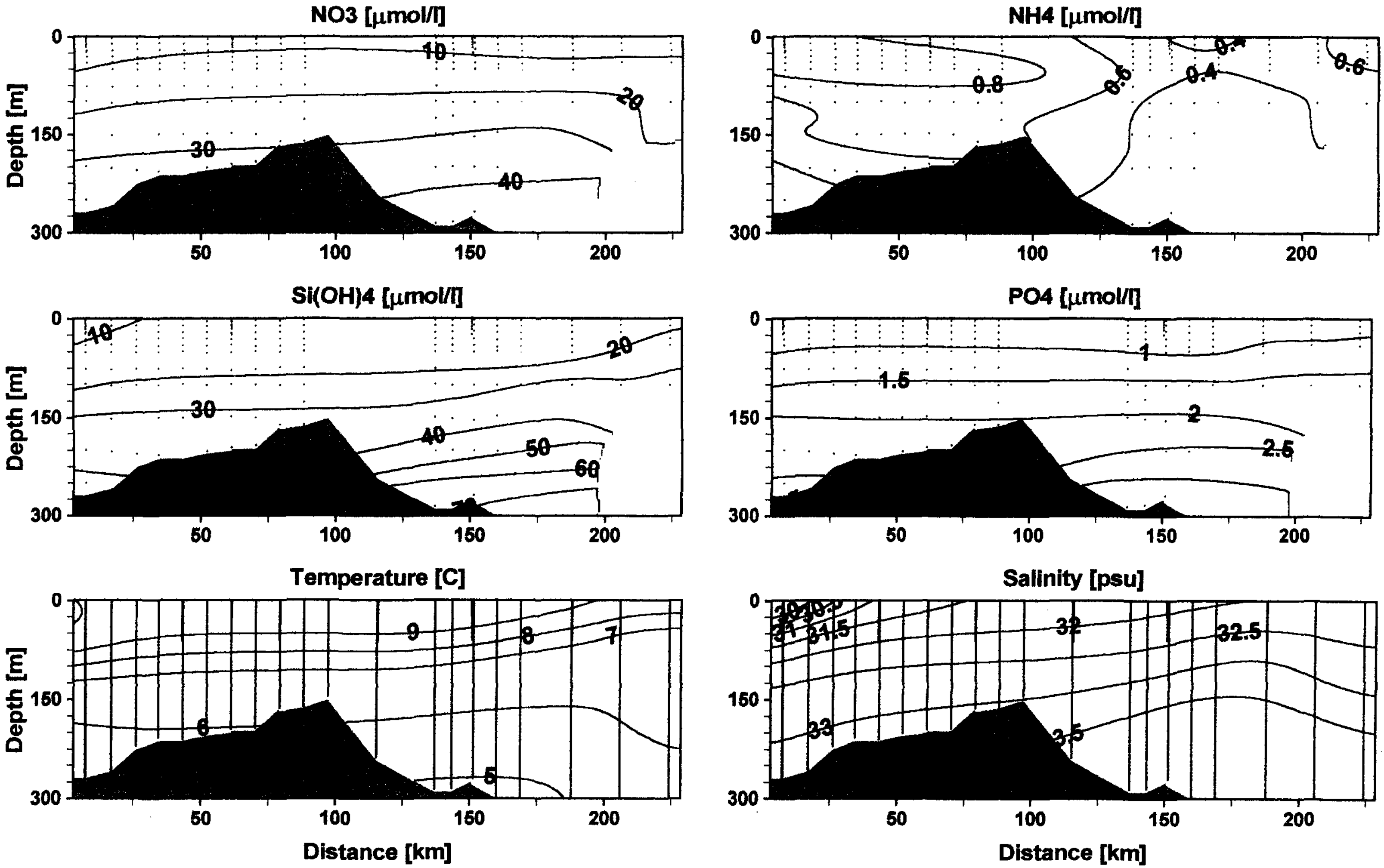

Fig. 3.8 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 5-9 October 1999. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).

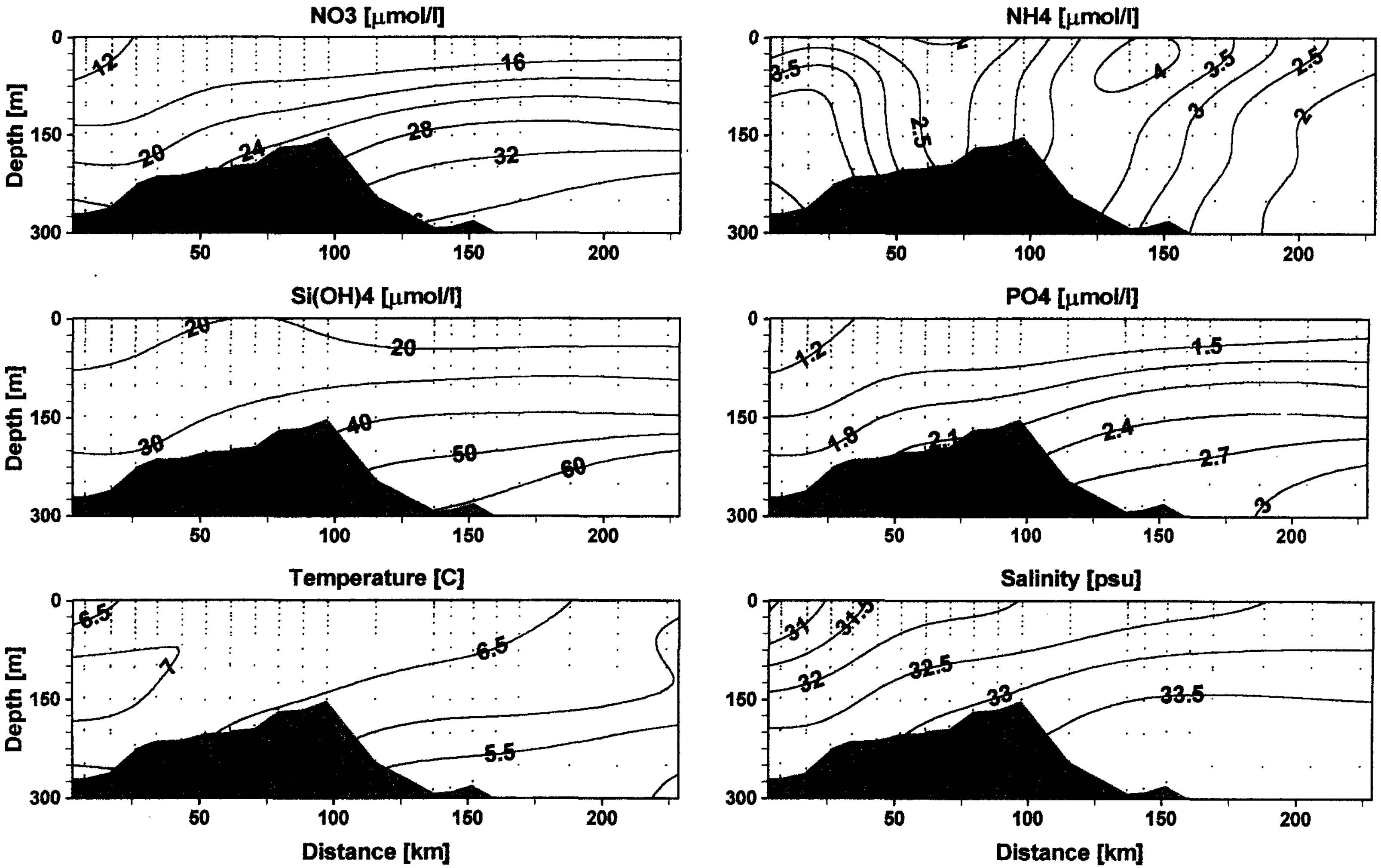

Fig. 3.9 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 2-4 December 1999. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).

inner shelf increased surface nitrate concentrations over the inner and middle shelf by December. A decrease in coastal discharge and strong cyclonic winds increased downwelling and produced deeper mixing, thereby enriching surface waters and decreasing nitrate concentrations below ~150 m from 25.0 to 33.0 μmole l^{-1} in October to 15.0 to 30.0 μmole l^{-1} in December. Offshore of the shelf-break, the nitrate concentrations continued to decrease from the maximum concentrations measured in August.

The December fluorescence profiles and chlorophyll *a* concentrations showed that phytoplankton biomass had increased slightly since October with mean surface and depth integrated chlorophyll *a* concentrations of 0.22 μg l^{-1} and 10.50 mg m^{-2} (Fig. 3.5). The surface and integrated chlorophyll *a* concentrations were evenly distributed across the inner and middle shelf with nearly double the concentrations over the outer shelf and oceanic regime.

3.1.4 1999 annual cycle of nutrients

The distributions and annual cycles of silicate and phosphate were very similar to nitrate. In general, silicate and phosphate concentrations were directly related to salinity, which increased with depth and distance offshore.

In spring (March and April) silicate and phosphate were uniformly distributed throughout the water column with high depth integrated concentrations for the year (Fig. 3.2, 3.3, 3.4). Lower silicate and phosphate concentrations were measured over the outer shelf and oceanic regimes in April. March and April ammonium concentrations were low, < 0.5 μmole l^{-1}, across the entire transect and throughout the entire water column.

Silicate and phosphate distributions in May mimicked the nitrate distributions with reduced concentrations over the inner shelf, outer shelf, and off shelf regimes and depth integrated silicate concentrations reached their annual maximum over the middle shelf in May (Fig. 3.4, 3.6). Ammonium concentrations remained low, < 1.0 μmole l^{-1}, except for slightly higher concentrations over both the inner shelf and shelf-break.

Silicate and phosphate distributions in August also mirrored the nitrate distributions, with minimum concentrations at the surface and maximum concentrations at depth (Fig. 3.7). The surface waters, above10 m, across the shelf contained < 6.0 μmole l^{-1} $Si(OH)_4$ and < 0.5 μmole l^{-1} PO_4^{-3}. As mentioned earlier, nutrient depletion is recognized when concentrations are reduced to less than twice the half-saturation constant (K_S). The general range in K_S for some phytoplankton is 0.5-5.0 μmole l^{-1} for silicate and 0.02-0.50 μmole l^{-1} for phosphate (LALLI and PARSONS, 1993). Using these criteria, some of the phytoplankton species in the surface waters may have approached or reached limiting silicate and phosphate concentrations. Depth integrated silicate and phosphate within the shelf regimes were at annual minimum concentrations, with the lowest concentrations occurring over the inner shelf and off shelf regimes (Fig. 3.4). At depth, elevated silicate and phosphate concentrations occurred over the shelf and offshore of the shelf-break. Over the inner and middle shelf, below ~150 m, annually high silicate (28-50 μmole l^{-1}) and phosphate (2.0-3.0 μmole l^{-1}) concentrations were measured as a part of the dense, nutrient-rich reservoir produced by the onshore flux. Ammonium concentrations had increased, with concentrations generally > 2.0 μmole l^{-1}, and with a region of high concentrations, greater than 3.0 μmole l^{-1} over the shelf-break.

Silicate and phosphate distributions in October were similar to the nitrate distributions, with relatively low surface concentrations, especially within the ACC (Fig. 3.8). However, depth integrated silicate and phosphate concentrations indicated replenishment of the upper 50 m compared to the low values measured in August (Fig. 3.4). Ammonium concentrations decreased after August and were relatively uniform across the transect with concentrations < 1.0 μmole l^{-1}.

Silicate and phosphate distributions in December displayed further replenishment of the upper water column (Fig. 3.9). Depth integrated silicate concentrations indicated replenishment within the upper 50 m for the shelf stations but not offshore. Except for the shelf-break, these concentrations appeared similar to those measured in March (Fig. 3.4). The depth integrated phosphate concentrations in December were higher, however, than those measured the previous March (Fig. 3.4). Ammonium concentrations increased across the transect and developed into patches, with concentrations > 4.0 μmole l^{-1} over both the inner shelf and the outer shelf.

3.2 Interannual variability in nutrient concentrations across the Seward Line

3.2.1 Annual variability between 1998 and 1999

There were distinct interannual differences in the chemical and physical properties across the Gulf of Alaska shelf in 1998 and 1999. Climatic effects must be considered, since 1997-1998 were strong El Nino years and the 'warm' phase of the Pacific Decadal Oscillation (PDO) shifted into the 'cool' phase sometime in 1999-2000 (NOAA, 2001; NASA, 2000). These climatic phases affect the atmospheric and oceanic conditions; therefore, they must be taken into account. The physical structure over the shelf is also affected by the speed and locations of shelf flows and by eddy activity, which differ from one year to the next. Therefore, this data set is comprised of two distinct years resulting from the interannual variability that has possibly been enhanced by interactive phases of ENSO and the PDO.

3.2.1.1 Late winter and spring

The winter of 1997-1998 featured strong downwelling winds and above average freshwater inputs, which created a relatively stable water column by generating a freshwater wedge along the coast (WEINGARTNER, personal communication). This freshwater wedge or lens suppressed mixing of nutrients up into the water column. Conversely, the following winter featured moderate winds and below average freshwater discharge, which resulted in weaker stratification and enhanced vertical mixing (WEINGARTNER, personal communication). These differing climatic conditions may explain the dissimilar nutrient, temperature, and salinity distributions measured in the spring of 1998 and 1999.

In general, the upper 100 m across the Seward Line were warmer (by ~1.0-1.5°C) and fresher (by ~0.5-2.0 psu) throughout March, April, and May of 1998 in comparison to 1999. The nitrate concentrations in the upper 100 m were consistently higher in spring

1999 than spring 1998, by as much as 30%. The upper water column nitrate concentrations in spring 1998 were reduced over the shelf-break in March and over the inner and outer shelf in April and May, which is a different pattern from that measured in spring 1999. Silicate concentrations in the upper 100 m varied seasonally and interannually, with highest concentrations in March of 1999 and April of 1998. Phosphate and ammonium concentrations in the upper 100 m, on the other hand, were consistently higher throughout spring 1998 than 1999.

Both May 1998 and 1999 had peak depth integrated nitrate concentrations over the middle shelf. This may have been due to eddy activity over the shelf, which as suggested by the salinity, temperature, and density profiles that displayed doming isopleths indicated upwelling. Also in May of both years, averaged nitrate concentrations offshore of the shelf-break below 500 m increased throughout spring, reaching high concentrations in May, with a mean of 43 μmole l^{-1} in 1998 (1998 annual maximum) and 48 μmole l^{-1} in 1999.

Surface and depth integrated chlorophyll *a* concentrations were notably higher throughout the spring of 1998 compared to 1999. March, April, and May 1998 depth integrated chlorophyll *a* mean concentrations were 14.7, 18.3, and 33.0 mg m^{-2}, respectively, compared to 1.6, 3.1, and 21.5 mg m^{-2} in 1999. May 1998 chlorophyll biomass was highest over the outer portion of the inner shelf, 60-100km offshore, with concentrations as high as 69.5 mg m^{-2}.

3.2.1.2 Summer

Samples were collected in mid July 1998 and late August 1999, and so a significant seasonal time shift must be considered when comparing the two data sets. The onshore winds, during the summer months, tended to relax, decreasing the downwelling index. As summer progressed into fall, the freshwater influx and precipitation rates peaked, creating less dense surface waters. The difference between these two data sets may be explained by interannual variability and/or differing seasonal conditions.

In August 1999, the water column across the shelf was more stratified and the surface waters were fresher than July 1998, due to freshwater addition. The warm surface temperatures also extended deeper into the water column in August 1999, due to longer exposure to insolation. However, surface nitrate drawdown was more extensive in July 1998 than August 1999. Nitrate concentrations were < 15 μmole l^{-1} in the upper 50 m in 1998, but nitrate concentrations were < 28 μmole l^{-1} in August 1999. In addition, nitrate concentrations were ~30% higher in the waters deeper than 50 m over the shelf and offshore of the shelf-break in 1999 compared to 1998. Ammonium was evenly distributed, < 1.1 μmole l^{-1}, over the shelf in July 1998. However, ammonium concentrations were higher and patchy in August 1999.

The deep nitrate concentrations (offshore of the shelf-break below 500 m) reached maximum concentrations in August 1999. However, in 1998, the deep nitrate concentrations reached maximum concentrations in May and decreased through July. July 1998 and August 1999 both had maximum nitrate, silicate, and phosphate concentrations over the inner shelf (below ~150 m), thus forming a nutrient-rich reservoir over the inner shelf.

The chlorophyll *a* concentrations had seasonally high phytoplankton biomass across the transect both years, although 1998 was higher overall. July 1998 surface and depth integrated chlorophyll *a* concentrations were highest over the middle shelf and shelf-break and lowest in the oceanic regime. From spring to late summer 1999, the mean depth integrated chlorophyll *a* concentration increased to 27.8 mg m^{-2}. However, from spring to early summer 1998, the mean decreased slightly to 30.5 mg m^{-2}.

3.2.1.3 Fall and winter

In contrast to October 1999, when nutrient replenishment began, nitrate drawdown continued throughout the upper ~150 m over the inner shelf and the upper 75-100 m across the middle shelf and offshore in October 1998. Below ~100 m, nitrate concentrations across the shelf were considerably higher, by 25-50%, in 1999 than in 1998. The ammonium concentrations were higher in October 1998 than 1999 with the highest concentrations, ~2.0 μmole l^{-1}, over the outer shelf.

In fall, the chlorophyll *a* concentrations decreased dramatically compared to summer. The October 1998 depth integrated chlorophyll *a* concentrations (mean = 3.1 mg m^{-2}) were lower than those measured in October 1999 (mean = 5.1 mg m^{-2}), with the majority of the biomass over the inner shelf in 1998.

December 1998 nitrate concentrations in the upper ~75 m had been moderately replenished since October. However, these concentrations were still considerably lower than those measured in 1999. Overall, the nitrate concentrations across the shelf in the upper water column and at depth were markedly lower in 1998. Ammonium concentrations were also lower in 1998, < 1.0 μmole l^{-1} across the shelf, but with slightly higher concentrations, ~2.5 μmole l^{-1}, just offshore of the shelf-break throughout the water column. Chlorophyll *a* concentrations reached annual minimum concentrations in December 1998 (depth integrated mean = 0.7 mg m^{-2}), compared to a rebound in biomass in December 1999 to an depth integrated mean of 10.5 mg m^{-2}.

3.2.2 Time series analyses

The interannual differences between 1998 and 1999 will be further discussed by examining time series from stations within the various shelf regimes. Time series from the Seward Line stations GAK 1, GAK 4, GAK 6, GAK 9, and GAK 13 were chosen to represent the inner shelf, outer portion of the inner shelf, middle shelf, shelf-break, and offshore waters respectively (Fig. 3.1).

3.2.2.1 GAK 1: Inner shelf regime

The GAK 1 station is at the mouth of Resurrection Bay at a water depth of ~275 m. The time series at GAK 1 showed a well mixed water column in March of both years. At this time, the water column was warmer, fresher, and lower in nitrate and silicate in 1998 compared to 1999 (Fig. 3.10). As March progressed into April, the depth integrated nitrate concentrations decreased, but remained higher in 1999. In May 1998, the water column continued to warm and freshen and began to stratify due to low surface salinities. However, May 1999 had a well mixed water column with surface salinities > 31.5 psu. The depth integrated nitrate concentrations in May of both years were similar to those in

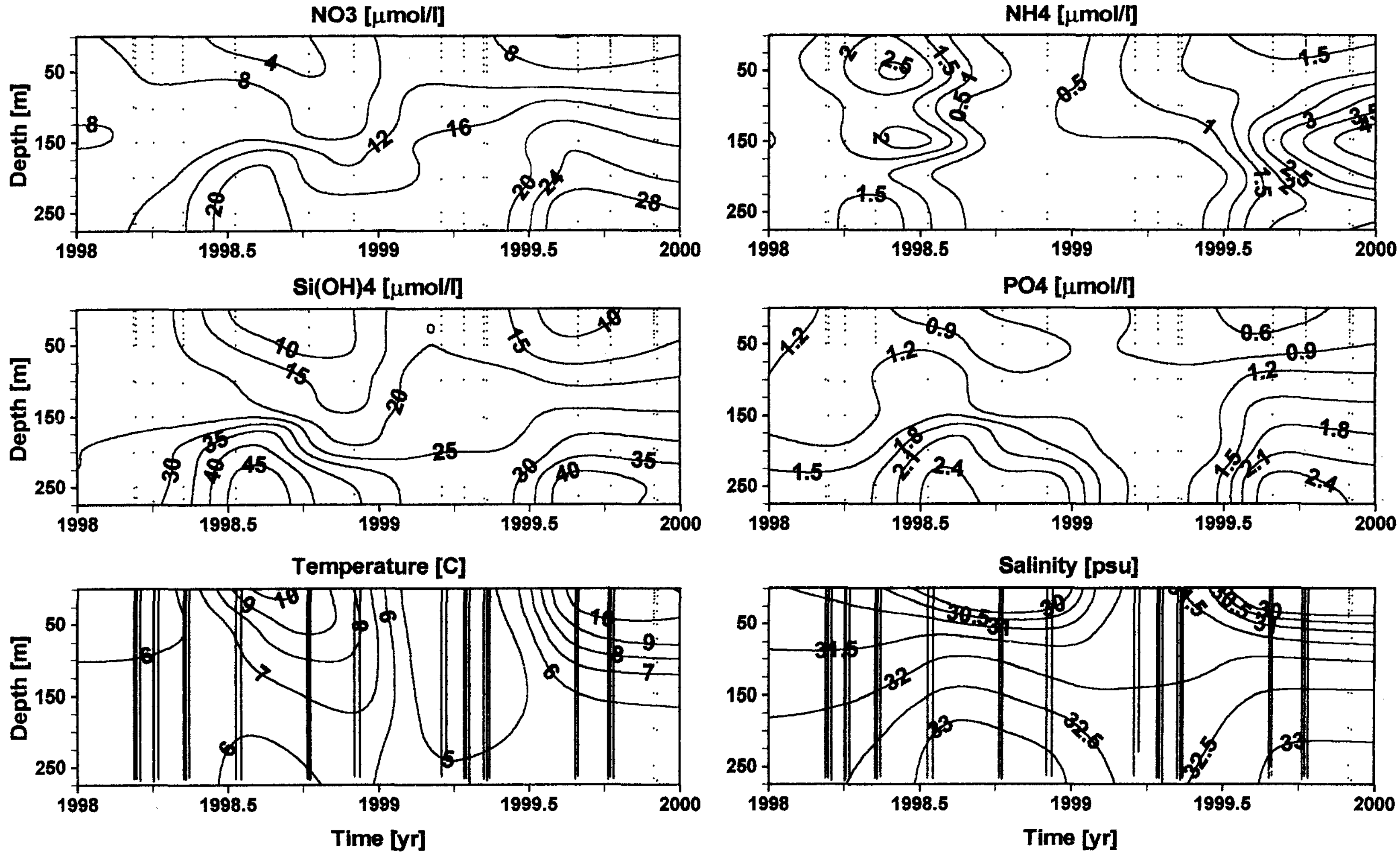

Fig. 3.10 A time series at GAK 1 of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity versus depth March 1998 – December 1999. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).

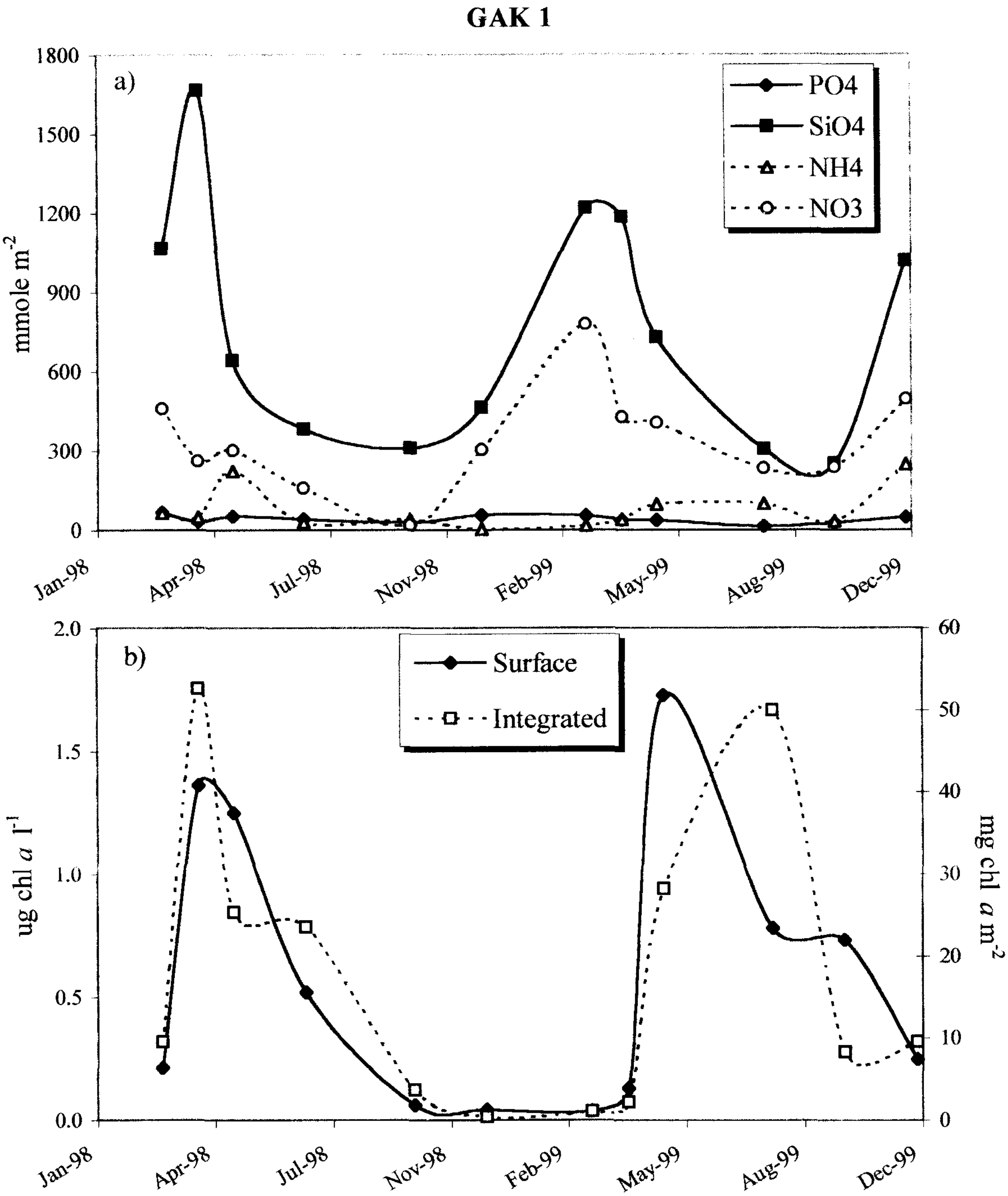

Fig. 3.11 A time series at GAK 1 of (a) integrated (0-50 m) nitrate, ammonium, silicate, and phosphate and (b) surface and integrated (0 to 30-50 m) chlorophyll *a* concentrations March 1998 – December 1999. Units are mmole m^{-2}, μg chl *a* l^{-1}, and mg chl *a* m^{-2}.

April, though nitrate concentrations continued to be higher in 1999 (Fig. 3.11). The silicate concentrations tracked the changes measured in nitrate, with the exception that silicate increased from March to April 1998 at the same time salinity decreased. Throughout spring, the depth integrated phosphate concentrations were at the annual maximum in May of both years, while depth integrated ammonium concentrations remained low and constant (Fig. 3.11).

July 1998 and August 1999 had a stratified water column with very warm, fresh surface waters accompanied by very saline, dense, and nutrient-rich bottom waters. The surface salinities within the ACC were fresher and extended deeper into the water column in August 1999 compared to July 1998. During these summer months, there was remarkable nitrate and silicate drawdown in the upper ~50 m. These extremely low surface nutrient concentrations were concurrent with annual maxima of bottom concentrations and salinities below 200 m, which is evidence of the onshore flux of nutrient-rich waters into the inner shelf.

October 1998 and 1999 showed further nitrate and silicate drawdown, which also extended deeper into the water column. The nutrient concentrations and salinities, below ~100 m, decreased more substantially from July to October 1998 than from August to October 1999. Finally in December, the water column was becoming more well mixed. The upper ~25 m salinity values were approaching 30.0 psu ,while the waters below ~100 m had decreased in salinity. The water temperatures in the upper ~75 m were also approaching those measured in March, with the warmest temperatures ~100 m. The depth integrated nitrate, silicate, and phosphate concentrations increased in December indicating the nutrients were being dispersed back into the upper water column by winter wind mixing. Overall, water column enrichment in nutrients by early winter mixing was greater in 1999 than 1998.

The total water column inventory for nitrate and silicate over the inner shelf was much higher in March 1999 than December 1998. Therefore there must have been an external nutrient source in addition to vertical wind mixing (Fig 3.10).

Chlorophyll *a* concentrations from the upper 50 m in March 1998 were relatively low, ~0.20 μg l^{-1}, and evenly distributed (Fig. 3.11). In April 1998, the biomass attained its annual maximum with surface and depth integrated concentrations of 1.36 μg *a* chl l^{-1} and 52.65 mg chl *a* m^{-2}, respectively. Thereafter, chlorophyll *a* gradually decreased over several months to the annual minimum in October and December. In 1999, the March and April chlorophyll *a* concentrations were very low throughout the upper 50 m. The biomass then increased in May, especially in the surface waters, which reached a maximum of 1.73 μg chl *a* l^{-1}. This surface enhancement was followed by a large decrease in biomass, which stabilized around 0.75 μg chl *a* l^{-1} in August and October. These concentrations finally dropped to 0.16 μg chl *a* l^{-1} in December. The depth integrated chlorophyll *a* concentrations, however, reached maximum concentrations in August (49.95 mg m^{-2}) and decreased dramatically in October, before rebounding slightly in December.

3.2.2.2 GAK 4: Outer portion of inner shelf regime

Station GAK 4 is situated ~60 km seaward of GAK 1 at the ~200 m isobath and generally represents the outer portion of the inner shelf, but may also be considered part of the middle shelf regime depending on the extent of the ACC. The time series at GAK 4 similarly had warmer, fresher, and lower nitrate waters in March and April 1998 compared to March and April 1999 (Fig. 3.12). The March 1998 salinity and temperature profiles displayed a well mixed upper ~100 m, which began to stratify in April 1998. In contrast, the 1999 salinity and nutrient profiles show that the entire water column was well mixed throughout spring. The nitrate concentrations were lower in spring 1998, but the silicate concentrations were similar or slightly higher in March and April of 1998. During the transition from March to April 1998, the depth integrated nitrate and silicate concentrations increased (Fig. 3.13). However, in May 1998, the depth integrated nitrate and silicate concentrations were reduced by ~50% and ~40% respectively. The depth-integrated nitrate and silicate concentrations in spring 1999 did not follow the 1998 trend. Instead, there was a general increase in nitrate and silicate from March through May.

As spring progressed into summer at GAK 4, the water column became more

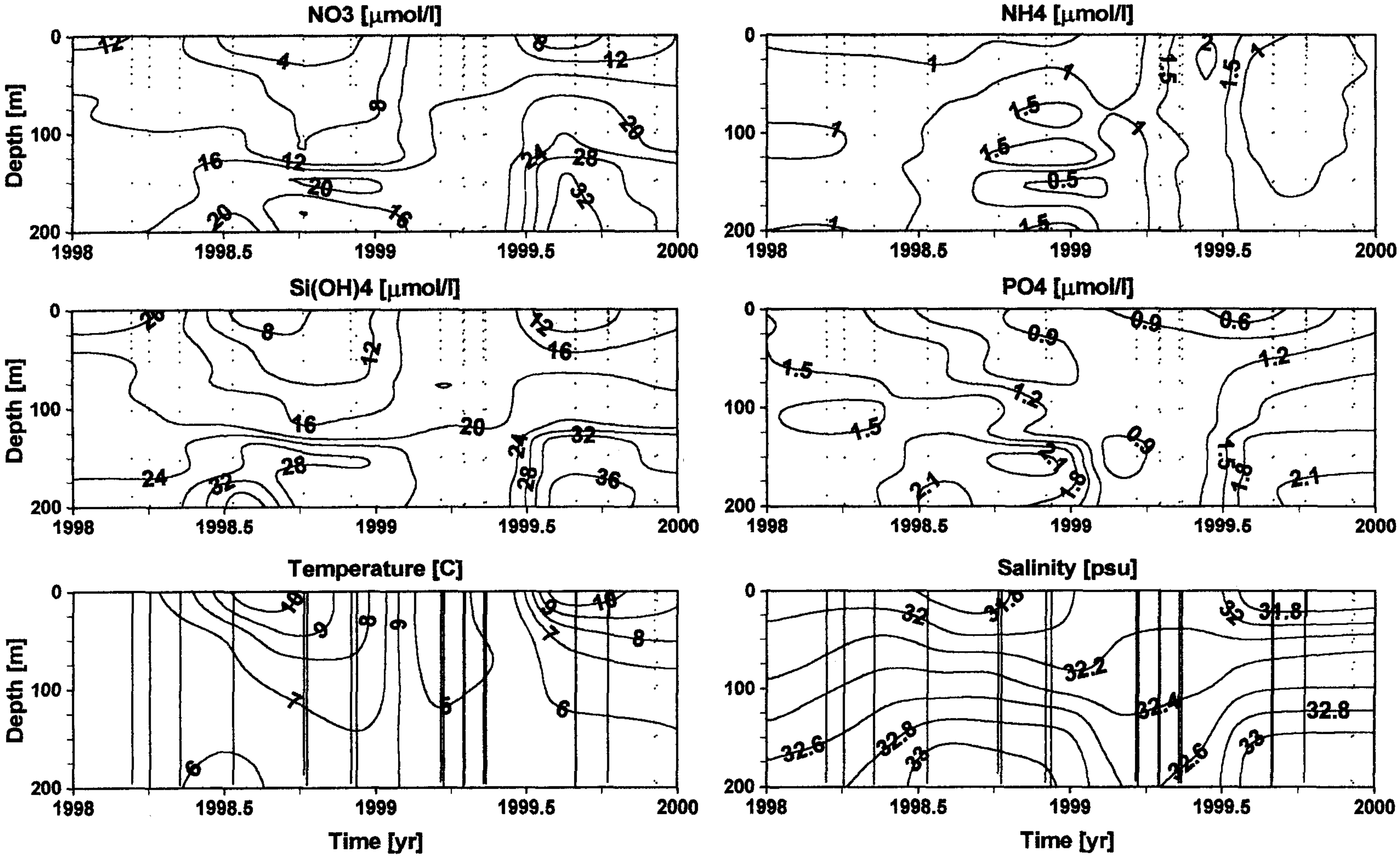

Fig. 3.12 A time series at GAK 4 of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity versus depth March 1998 – December 1999. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).

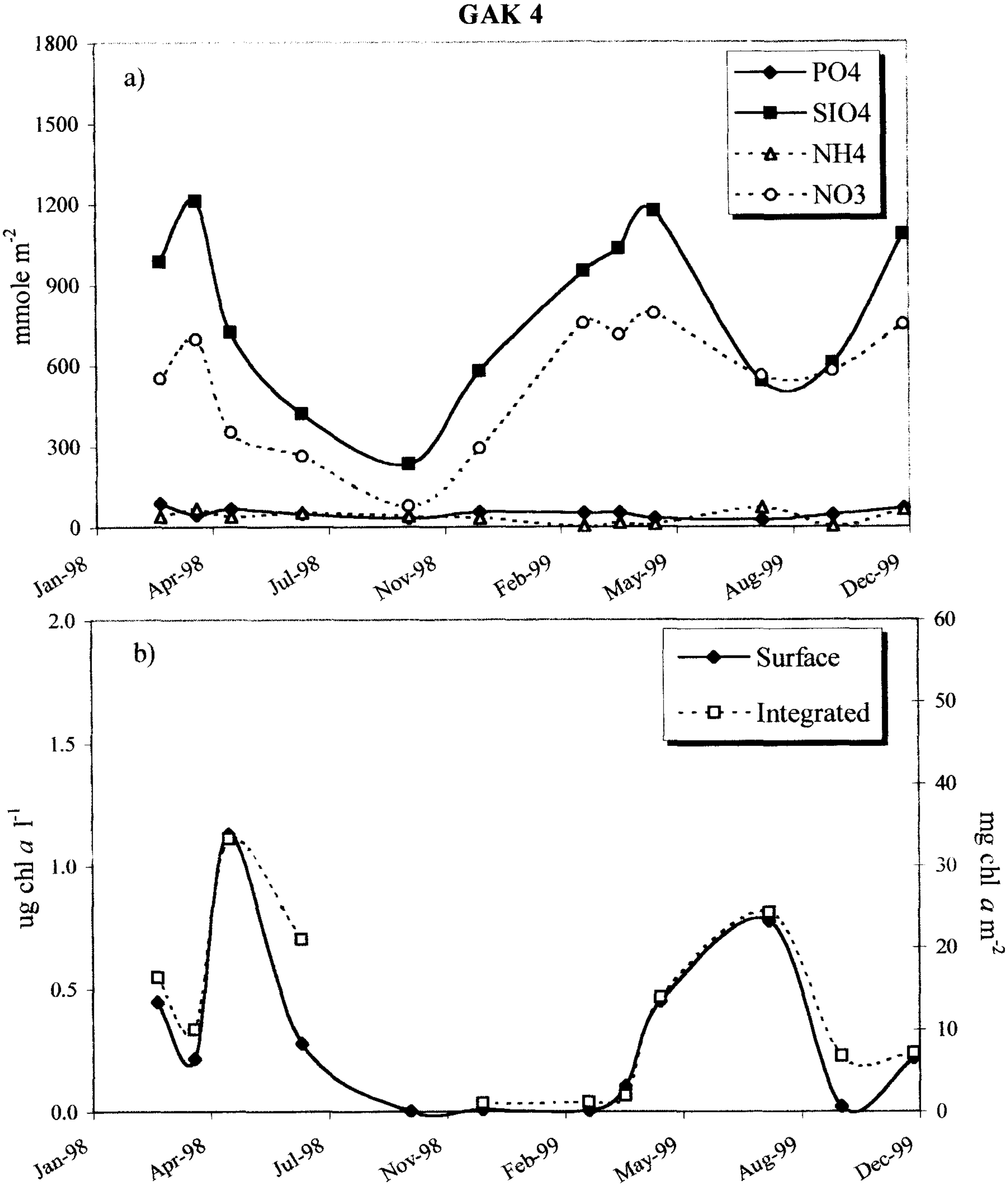

Fig. 3.13 A time series at GAK 4 of (a) integrated (0-50 m) nitrate, ammonium, silicate, and phosphate and (b) surface and integrated (0 to 30-50 m) chlorophyll *a* concentrations March 1998 – December 1999. Units are mmole m^{-2}, μg chl *a* l^{-1}, and mg chl *a* m^{-2}.

stable as the surface salinities decreased to ~31.5 psu, and the surface temperatures increased to ~13.0°C. Nutrient uptake was evident in the upper 25-50 m, especially in July 1998 when the nutrient drawdown was more extensive. The depth integrated nitrate, silicate, and phosphate concentrations decreased after May by ~25%, 42%, and 28% in 1998 and ~20%, 37%, and 29% in 1999, respectively. August 1999 also had the annual maximum of depth integrated ammonium concentrations. At depth, the waters below ~150 m reached maximum nutrient concentrations and salinities. These deep waters were higher in nitrate and silicate in August 1999 and higher in phosphate and salinity in July 1998.

Surface nutrient drawdown continued into October 1998. Over the course of this year, the depth integrated nitrate, silicate, and phosphate concentrations reached minimum levels in October (Fig. 3.13). October 1999, on the other hand, showed an increase in depth integrated nitrate and silicate concentrations since August 1999. The nitrate and silicate concentrations at depth had decreased since the maximum concentrations measured in July and August, particularly from July to October 1998. Finally in December 1998 and 1999, the water column was less stratified. Especially in 1998, the salinity and temperature profiles showed mixing down to ~100 m. The depth integrated nutrient concentrations all increased from October to December, and as measured at GAK 1 they were higher in December 1999 compared to December 1998.

Surface and depth integrated chlorophyll *a* concentrations at GAK 4 reached maximum concentrations in May 1998, 1.10 $\mu g\ l^{-1}$ and 33.3 $mg\ m^{-2}$ respectively, followed by a general decrease with minimum concentrations in October and December 1998 (Fig. 3.13). In contrast, phytoplankton biomass in 1999 increased throughout spring to reach maximum concentrations in August. This peak in biomass was followed by a decrease in October, then a slight rebound in surface water concentrations in December 1999 (0.22 μg chl *a* l^{-1}).

3.2.2.3 GAK 6: Middle shelf regime

Station GAK 6 is located ~95 km offshore, over the shallowest region of the transect in ~150 m of water. As measured over the inner shelf, the water column over the middle shelf in March and April 1998 was warmer, fresher, and lower in nitrate compared to 1999 (Fig. 3.14). The nutrient and salinity profiles showed a well mixed water column with some structure within the bottom layer, ~ 50 m thick, during the first few months of spring 1998 and 1999. As spring progressed into May 1998, the depth integrated nitrate concentrations increased from around 600 mmole m^{-2} to 1369 mmole m^{-2}, while depth integrated silicate generally decreased (Fig. 3.15). March, April, and May 1999, however, produced dissimilar trends in depth integrated nitrate and silicate, which decreased slightly in April, then rebounded in May to concentrations similar to those of March.

As summer progressed, the water column became more stratified. Surface temperatures reached 13°C in July 1998 and August 1999. However, these warmer temperatures extended deeper into the water column in August 1999. The surface salinities were lower in July 1998 , ~31.3 psu, than in August 1999, when surface salinities approached 31.8 psu. The depth integrated nitrate and silicate concentrations decreased markedly from May to summer both years, with the top 10 m depleted to concentrations < 1.0 μmole l^{-1} NO_3^-. As seen at GAK 1 and GAK 4, these low surface nutrient concentrations were accompanied by nutrient-rich, high salinity water at depth separated by a strong pycnocline. The nitrate concentrations in August were the highest measured at this station, reaching 45 μmole l^{-1}. Ammonium concentrations reached high concentrations at 2.4 μmole l^{-1} in August 1999.

October 1998 had continued surface nitrate and silicate utilization, while in October 1999 the nitrate and silicate concentrations in the surface waters were being replenished (Fig. 3.15). The salinity and temperature profiles showed stronger mixing in the upper water column in October 1999 than 1998, explaining the replenishment of nutrients to the upper water column. There was a decrease in deep nutrient concentrations following the high concentrations measured in July and August. In December 1998 and 1999, the upper 50 m were being replenished with nutrient concentrations notably higher in 1999.

The chlorophyll *a* concentrations were low throughout the upper water column in

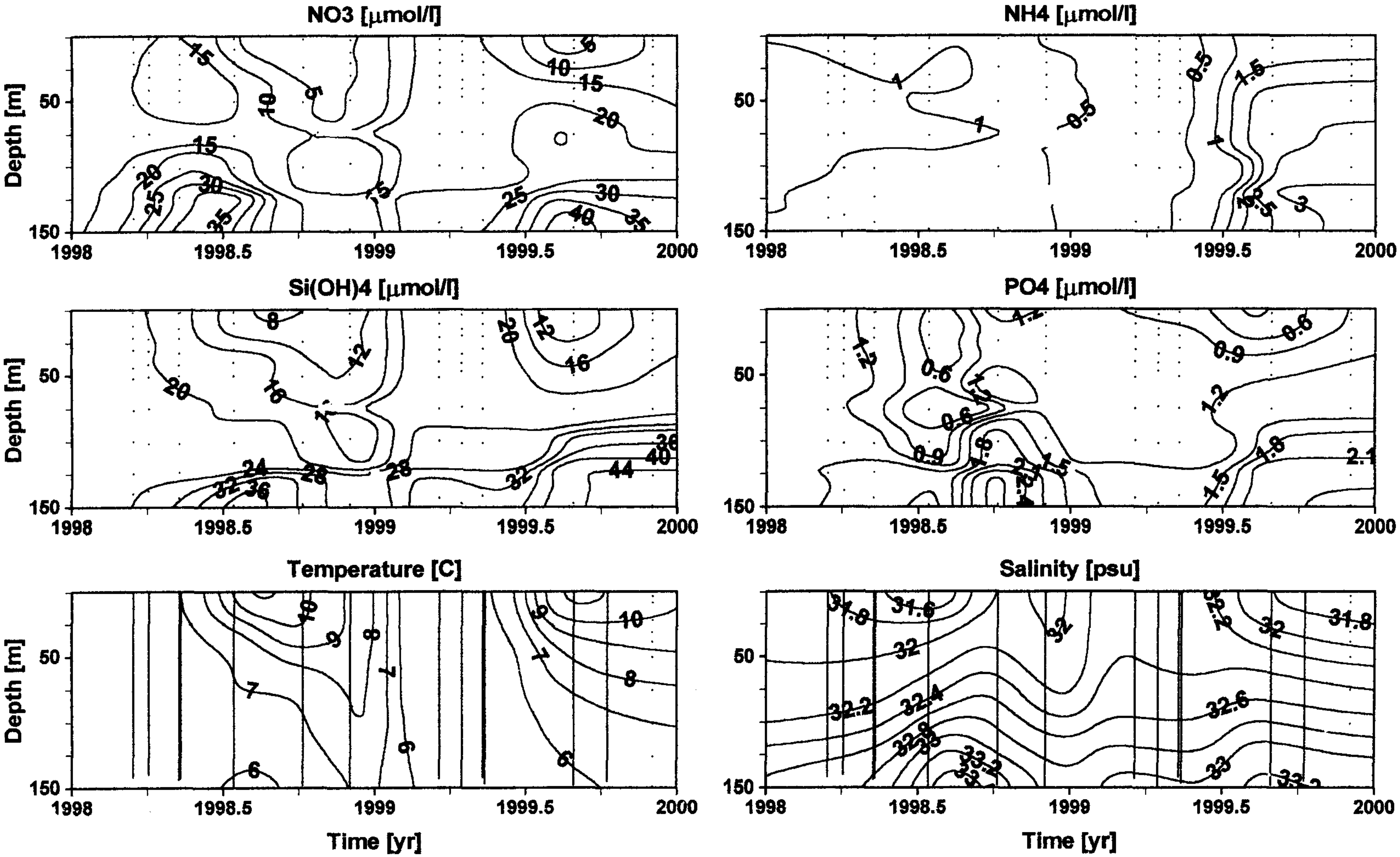

Fig. 3.14 A time series at GAK 6 of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity versus depth March 1998 – December 1999. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).

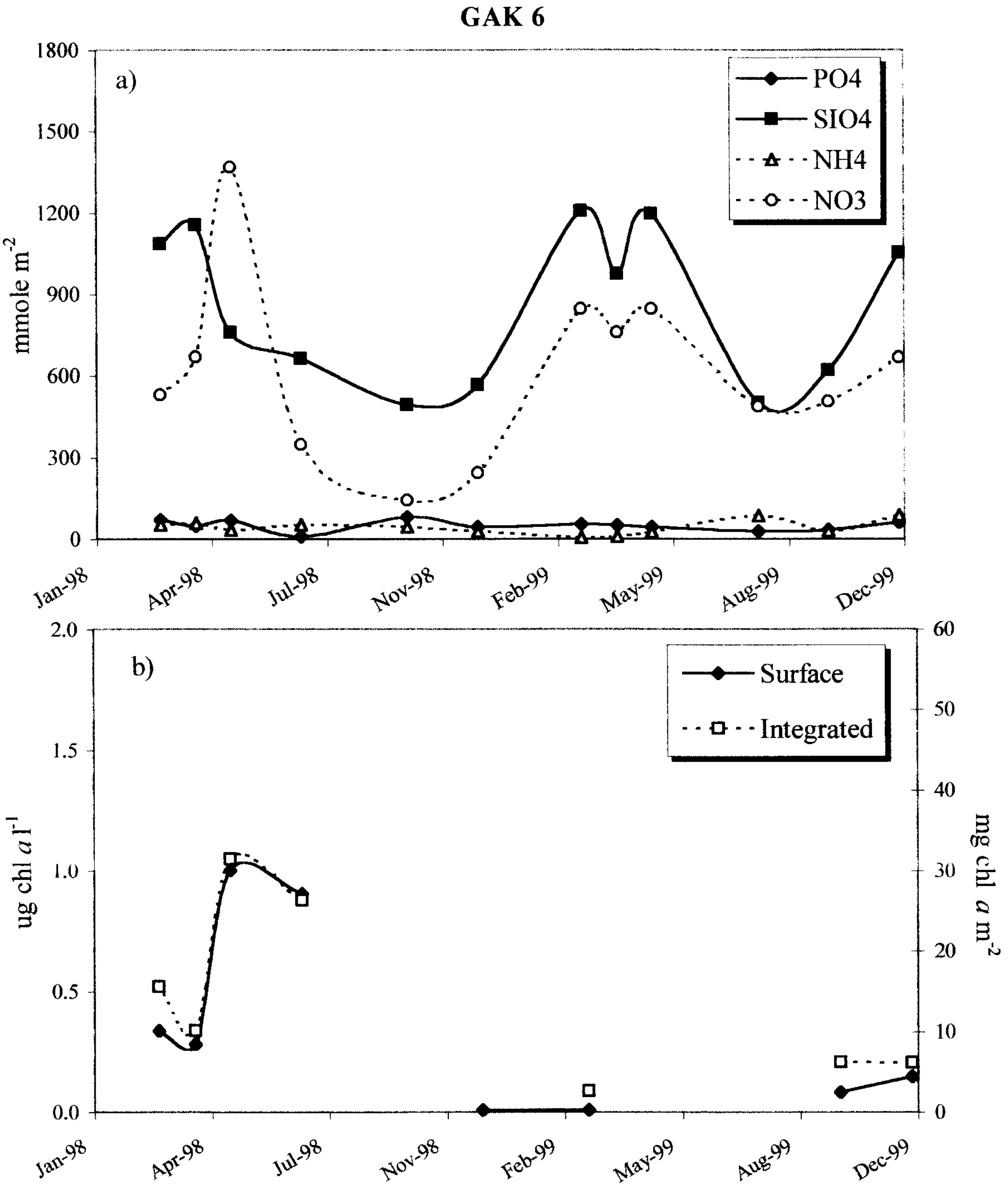

Fig. 3.15 A time series at GAK 6 of (a) integrated (0-50 m) nitrate, ammonium, silicate, and phosphate and (b) surface and integrated (0 to 30-50 m) chlorophyll *a* concentrations March 1998 – December 1999. Units are mmole m^{-2}, μg chl *a* l^{-1}, and mg chl *a* m^{-2}.

March and April 1998, but increased in May and reached annual maximum surface and depth integrated concentrations of 1.0 μg l^{-1} and 31.5 mg m^{-2} (Fig. 3.15). The surface chlorophyll *a* concentrations then dropped to the year's minimum concentrations in December 1998. The few spring chlorophyll *a* concentrations obtained from GAK 6 in 1999 were relatively low compared to spring 1998 (Fig. 3.15). Data from GAK 5i, just inshore of GAK 6, also had low surface and depth integrated chlorophyll *a* concentrations in March and April 1999. The GAK 5i depth integrated chlorophyll a concentrations increased to ~30 mg m^{-2} in May and August 1999, then decreased in October (12.1 mg m^{-2}) and December (5.2 mg m^{-2}).

3.2.2.4 GAK 9: Shelf-break regime

Station GAK 9 lies ~140 km offshore over the shelf-break at the ~275 m isobath. This site is situated over the shelf-break where frontal systems, shear, and onshore advection affect the physical and chemical distributions.

As measured over the rest of the shelf, the water column in March 1998 was warmer and fresher and lower in nitrate and silicate than March 1999 (Fig. 3.16). Curiously, the March 1998 water column contained the lowest salinity values for this station. Thereafter, the salinity increased by ~1.0 psu throughout the water column in April, and finally decreased to salinities between the extremes measured in March and April 1998. The spring 1999 salinity profiles were all similar to one another, although there was a small increase in salinity throughout the water column from March to May. The depth integrated nitrate concentrations in spring 1998 were maximal in April, but this was not reflected in the silicate concentrations (Fig. 3.17). Overall, spring 1998 depth integrated nitrate, silicate, and phosphate concentrations displayed a general increase, while in spring 1999 there was a general decrease in surface nutrient concentrations. These spring months also had very low ammonium concentrations throughout the water column both years.

The nitrate and silicate concentrations increased from March to May in the deeper water column (> 150 m) in both 1998 and 1999. In May 1998, the annual maximum in nitrate (48.9 μmole l^{-1}) and silicate (78.5 μmole l^{-1}) concentrations were measured near

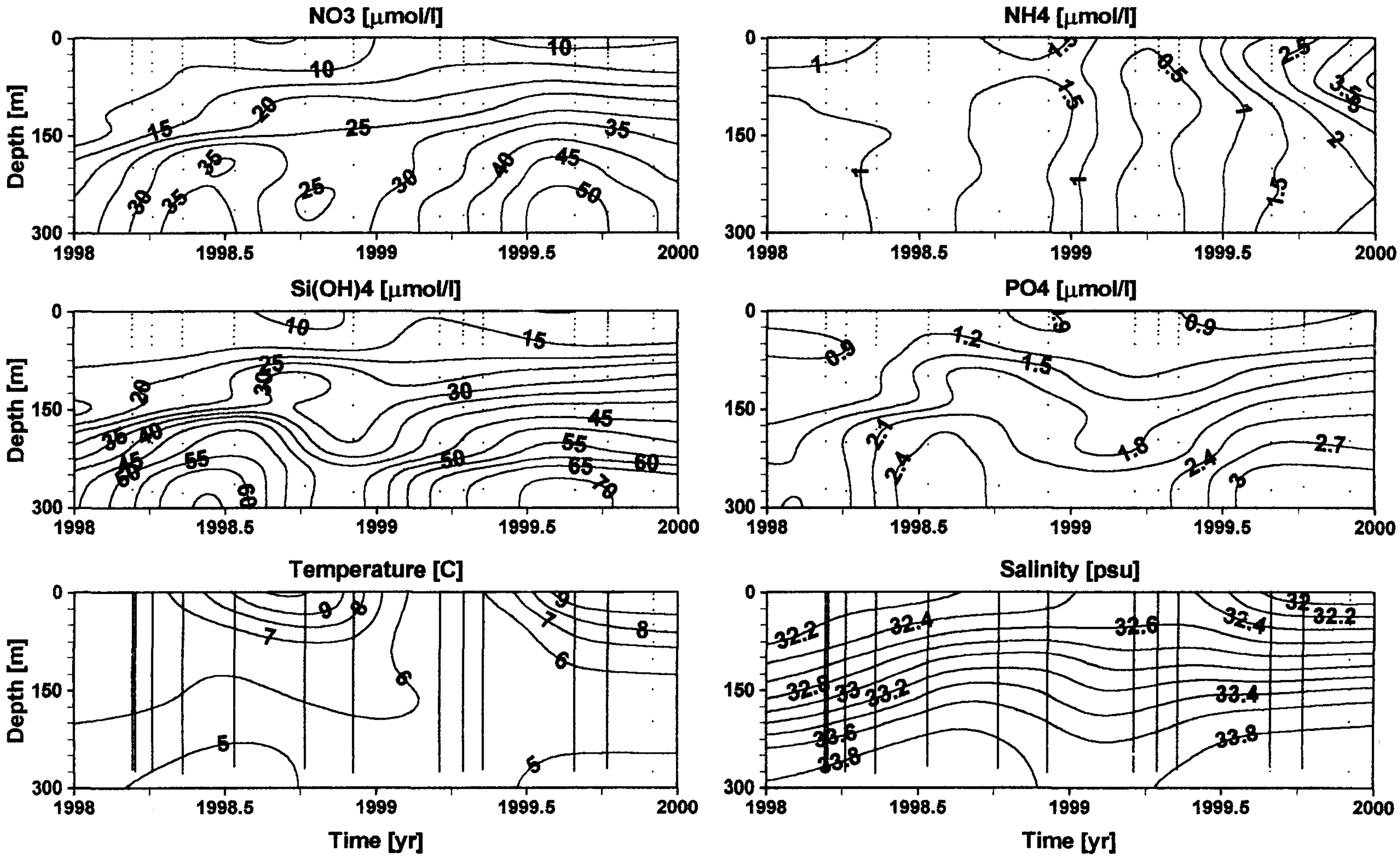

Fig. 3.16 A time series at GAK 9 of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity versus depth March 1998 – December 1999. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).

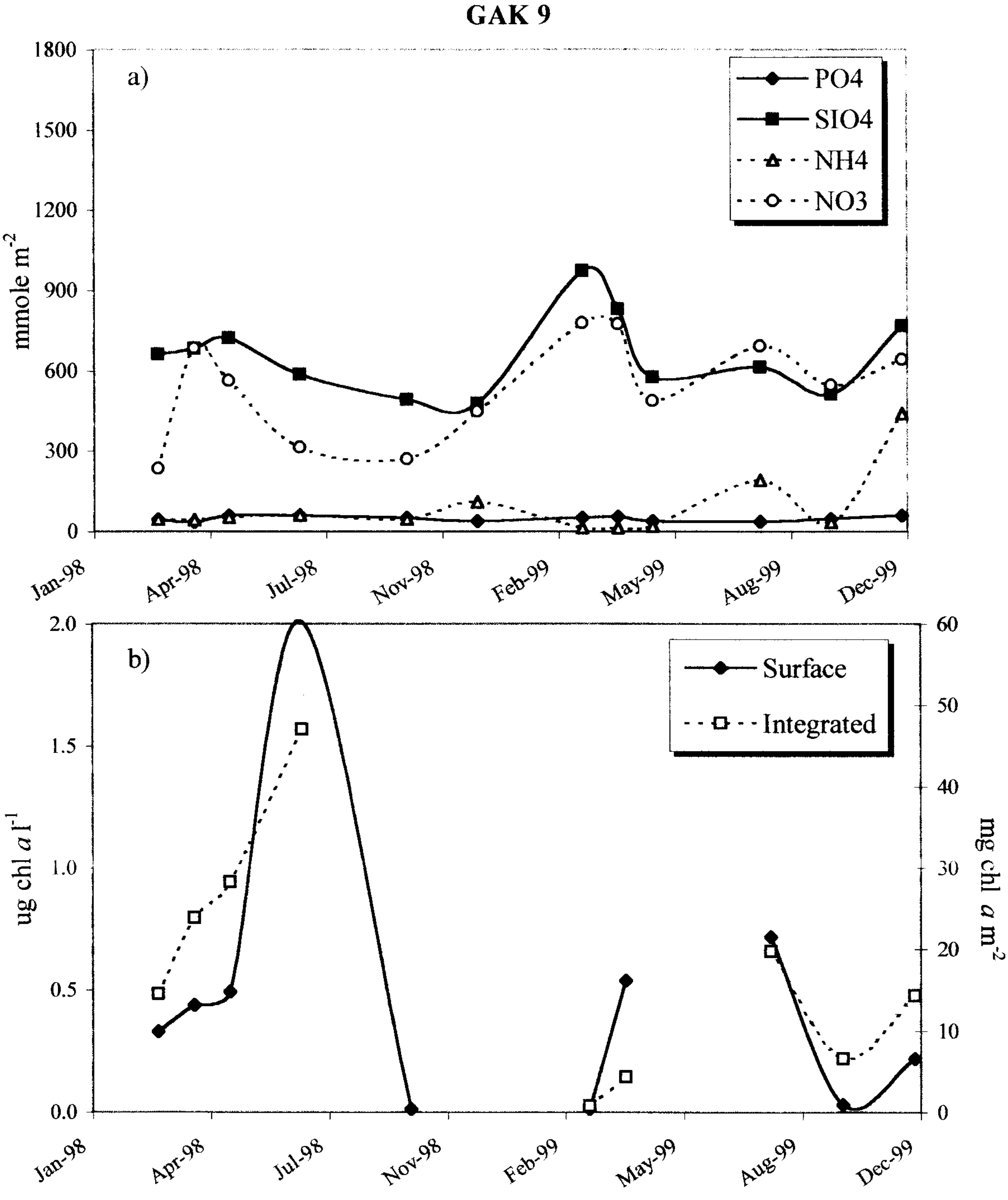

Fig. 3.17 A time series at GAK 9 of (a) integrated (0-50 m) nitrate, ammonium, silicate, and phosphate and (b) surface and integrated (0 to 30-50 m) chlorophyll *a* concentrations March 1998 – December 1999. Units are mmole m^{-2}, μg chl *a* l^{-1}, and mg chl *a* m^{-2}.

the bottom (~275 m) at GAK 9. The bottom concentrations increased through March and April and peaked in May, then decreased through October and December 1998. In 1999, however, the nutrient concentrations did not peak until August.

The spring to summer transition period at the shelf-break involved a decrease in depth integrated nutrient concentrations from May to July 1998, but an increase in depth integrated nitrate and silicate from May to August 1999 (Fig 3.17). In both July 1998 and August 1999, nitrate depletion occurred in the upper ~10 m where nitrate concentrations were < 1.0 μmole l^{-1}. While nitrate depletion and silicate and phosphate drawdown occurred in the upper 10 m, the depth integrated nutrient concentrations increased in August 1999. This was accompanied by relatively high ammonium concentrations in the upper ~40 m and the lowest surface salinities in the upper ~20 m measured at this station.

These upper water column dynamics occurred along with changing bottom concentrations. The 1998 nitrate and silicate concentrations below ~200 m declined from the peak in May. However, in July the waters above ~200 m had increased in nitrate, silicate, and salinity as the bottom waters mixed up into the water column. The bottom concentrations were relatively high in May 1999. However, August 1999 had the annual maximum bottom concentrations, when the nitrate concentrations reached ~48.0 μmole l^{-1} and silicate reached 74.9 μmole l^{-1}.

October 1998 showed continued nutrient utilization at the shelf-break as the depth integrated nitrate, silicate, and phosphate concentrations decreased after July 1998. Similarly, depth integrated nitrate and silicate over the shelf-break also decreased between August and October 1999. Nutrient concentrations at depth continued to decrease after the maxima detected in May 1998 and August 1999. Finally in December of both years, there was a general increase in depth integrated nutrient concentrations, which were higher overall in 1999. In December 1999, the nitrate and silicate concentrations in the upper 150 m increased while those below 150 m decreased. Overall, the waters below 50 m generally had higher nitrate and silicate concentrations throughout the year in 1999 than 1998, except for the extreme high in May 1998.

The chlorophyll *a* concentrations from GAK 9 slowly increased from March to May 1998, with mean surface concentrations of 0.42 μg l^{-1} and mean depth integrated concentrations of 22.9 mg m^{-2} (Fig. 3.17). Peak chlorophyll *a* concentrations were reached in July with the highest concentrations at ~10 m, reaching 2.39 μg l^{-1}. The surface chlorophyll *a* concentrations then dropped to very low concentrations in October 1998. In 1999, the chlorophyll *a* concentrations were low in March and April, however there was a small increase in surface chlorophyll *a* in April. Chlorophyll *a* concentrations for May 1999 at GAK 9 are lacking, but data from GAK 8i (~12 km farther inshore) have high depth integrated concentrations (46.9 mg chl *a* m^{-2}). At both stations, there was a decrease in biomass after August, which rebounded slightly in December 1999.

3.2.2.5 GAK 13: Outer shelf oceanic regime

Station GAK 13 lies beyond the shelf-break ~230 km offshore, within the offshore or oceanic regime at the ~2100 m isobath. This station was not sampled during the April 1998 cruise due to unfavorable weather conditions. The temperature and salinity profiles of the water column in March and April showed that the upper ~15 m were well mixed in 1998. However, in 1999 the water column was well mixed down to 100 m (Fig. 3.18). Probably as the result of El Nino conditions in early spring 1998, the surface salinities were lower and the surface temperatures were higher than those that were mixed throughout the upper ~100 m in March 1999. March 1998 had lower nitrate concentrations, yet slightly higher silicate concentrations in the upper ~100 m than March 1999. Below ~100 m, nitrate and silicate were higher in March 1999 than March 1998. Integrated nutrient concentrations from the upper 50 m in March had lower nitrate and higher silicate and phosphate in 1998 compared to 1999 (Fig. 3.19). The depth integrated nitrate and silicate concentrations did not follow the same general trend as closely as they did at the shelf and shelf-break stations. Overall, there was a general decreasing trend in the upper 50 m in the nutrient concentrations from March through May 1998 and 1999. May of both years had nitrate and silicate drawdown, with concentrations in the upper ~25 m less than 9.5 μmole l^{-1} and 16.0 μmole l^{-1}, respectively. The nitrate, silicate, and

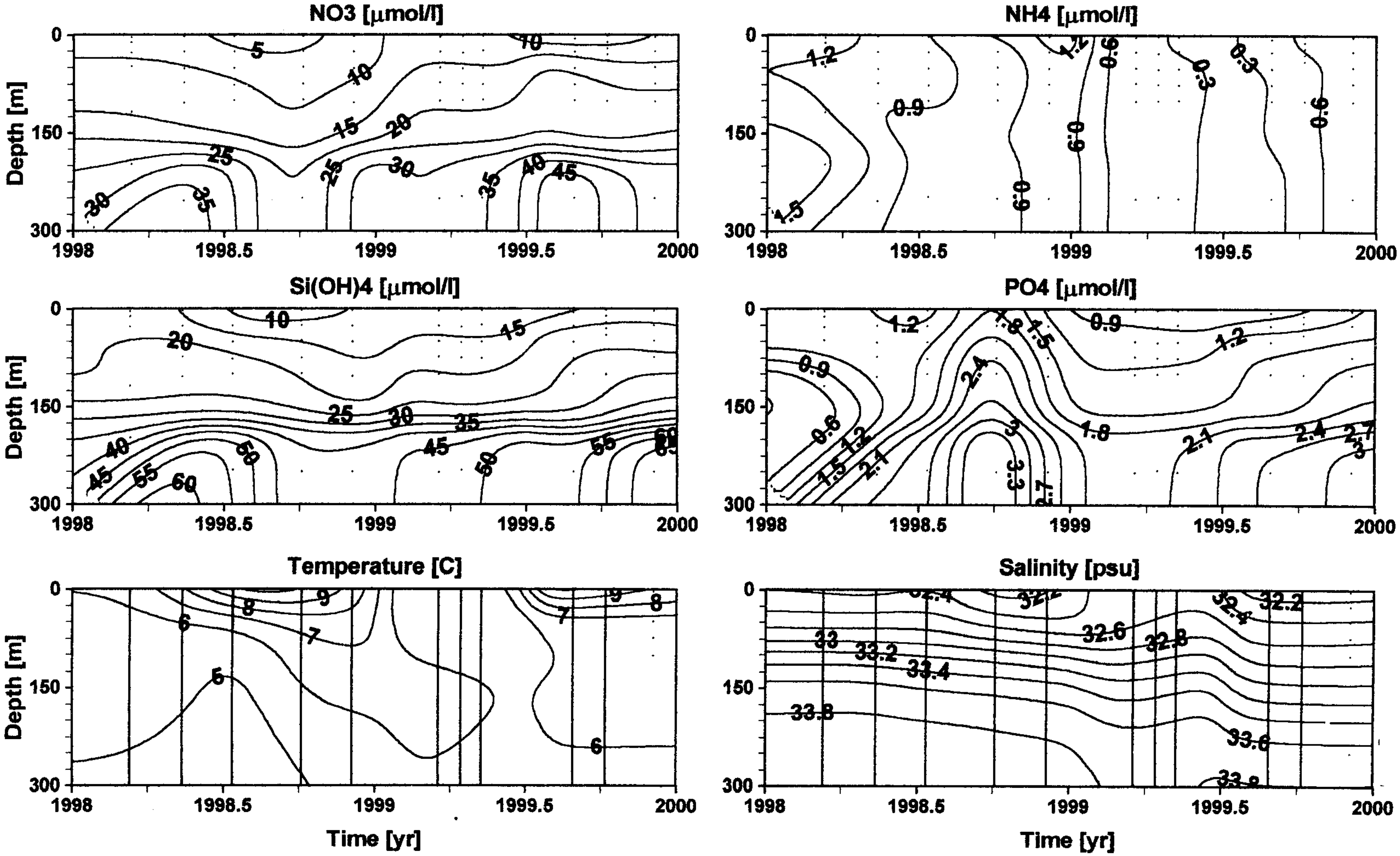

Fig. 3.18 A time series at GAK 13 of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity versus depth March 1998 – December 1999. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).

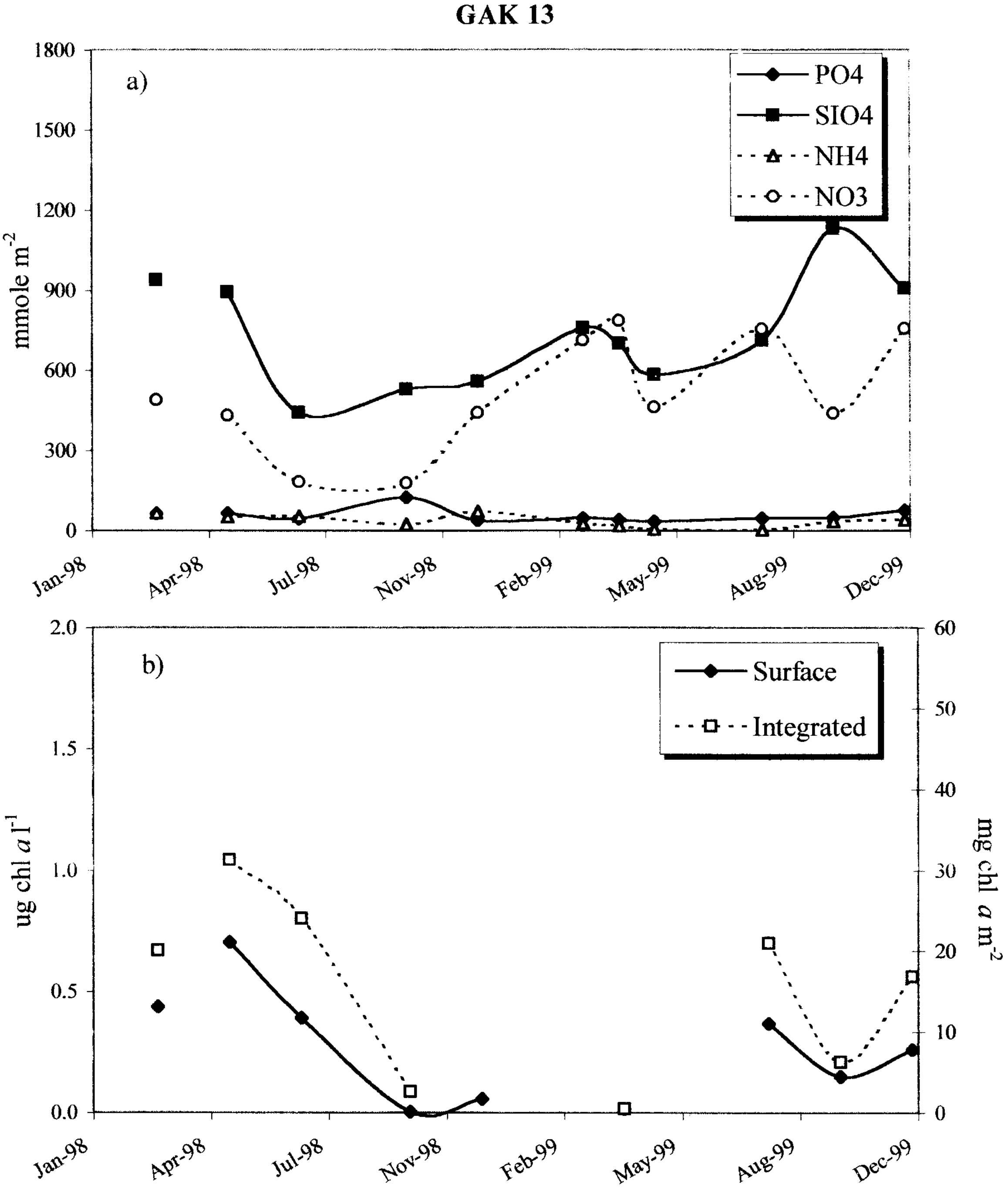

Fig. 3.19 A time series at GAK 13 of (a) integrated (0-50 m) nitrate, ammonium, silicate, and phosphate and (b) surface and integrated (0 to 30-50 m) chlorophyll *a* concentrations March 1998 – December 1999. Units are mmole m^{-2}, μg chl *a* l^{-1}, and mg chl *a* m^{-2}.

phosphate concentrations increased from March to May below the upper mixed layer (> 75 m), especially in 1999.

July 1998 and August 1999 had the highest surface temperatures, which reached 12.3°C in 1998 and 13.3°C in 1999. July 1998 salinities in the upper 40 m increased since May, but August 1999 surface salinities were at annual minimum values, ~31.9 psu. Nutrient drawdown continued throughout the summer months in the upper 10-20 m. In July 1998, nitrate and silicate drawdown extended throughout the upper ~75 m, while in August 1999, the nitrate and silicate concentrations below ~25 m depth increased, as shown in the depth integrated concentrations (Fig 3.19). Through the course of each year, large fluctuations were found in the nutrient concentrations from depths > 500 m below the permanent halocline (~20 μmole l^{-1} nitrate, ~100 μmole l^{-1} silicate, and ~1.0 μmole l^{-1} phosphate).

As summer progressed into fall, the upper ~75 m decreased in salinity, especially the top ~25 m in October 1998, which also decreased in temperature to ~10.6°C. However, the October 1999 salinity and temperature profiles remained very similar to the August 1999 profiles, except the top ~25 m temperatures decreased to ~8.7 °C. Overall the upper water column was warmer and fresher in October 1998. In common with the rest of the shelf in October, the 1998 low surface nitrate and silicate concentrations now extended deeper, to 75-100 m, while the nutrients in the upper ~25 m were replenished in 1999. At depths below ~75 m, nitrate and silicate concentrations had decreased since summer.

The upper water column was well mixed in December 1998 and 1999, with cooler temperatures and higher salinities. The upper water column nutrients were finally being replenished in 1998 and continued to be replenished in 1999. The depth integrated nitrate, silicate, and phosphate concentrations were higher in December 1999 than December 1998 and were already greater than those measured the preceding March 1999. At depths > 500 m, December 1998 had annual maximum nitrate concentrations of ~45 μmole l^{-1}, while December 1999 had the annual maximum silicate concentrations which reached 163.1 μmole l^{-1} at 1500 m.

Throughout 1998, the water column at GAK 13 was warmer, fresher, and lower in nutrients than in 1999. Mixing of the upper water column was more extensive in spring 1999 and the flux of nutrients into the upper water column extended higher into the water column in fall and winter 1999. The ammonium concentrations were low and relatively uniform, < 1.5 μmole l^{-1}, throughout the water column during both 1998 and 1999.

Chlorophyll *a* concentrations at GAK 13 throughout 1998 and 1999 were relatively low compared to the other shelf regimes, with < 0.70 μg l^{-1} in the surface waters and < 31.0 mg m^{-2} integrated over the upper 50 m (Fig. 3.19). The 1998 chlorophyll *a* data showed high biomass in May, which gradually decreased throughout summer and fall. The 1999 data showed summer surface and depth integrated chlorophyll *a* concentrations similar to summer 1998, which decreased through October, then rebounded slightly in December 1999.

To summarize, the five stations within the four shelf regimes all had warmer, fresher water columns, as well as lower nutrients concentrations in 1998 compared to 1999. The nutrients generally decreased throughout the spring months, while the chlorophyll *a* concentrations increased, although there were a few instances where the depth integrated nutrient concentrations increased through May. Depth integrated nitrate and silicate concentrations decreased from spring to summer across the transect in 1998 and over the shelf in 1999. However, in 1999 they increased during this time period over the shelf-break and outer shelf. Depth integrated nitrate and silicate concentrations continued to decrease through October 1998 (except silicate at GAK 13) and reduced concentrations extended deeper into the water column (50-100 m). In October 1999, the depth integrated nitrate and silicate concentrations also decreased over the inner shelf and shelf-break (including nitrate at GAK 13), but the other stations showed replenishment of the upper water column. By December of both years, the upper 50 m was being replenished (except silicate at GAK 13) with higher depth integrated concentrations in December 1999 compared to December 1998.

The chlorophyll *a* concentrations had maximum concentrations in May and July/August of both years. Across the shelf, the highest surface chlorophyll *a* concentrations were over the inner shelf and shelf-break. At GAK 1 in 1998, the spring bloom appeared earlier than over the rest of the shelf, with the highest surface and depth integrated concentrations in April. At GAK 1 in 1999, the spring bloom appeared in May, with maximum surface chlorophyll *a* concentrations which continued through summer and with maximum depth integrated concentrations in August. Over the middle shelf (GAK 4 and GAK 6) the bloom did not appear until May 1998, after which the phytoplankton biomass gradually decreased through summer and fall. However, in 1999 the biomass continued to increase to maximum concentrations in August at GAK 4. Over the shelf-break, the maximum surface and depth integrated chlorophyll *a* concentrations were reached in July 1998. By fall and early winter, the chlorophyll *a* concentrations were minimal in 1998, but in 1999 they were low then rebounded in December.

3.3 The relationship between salinity and the major nutrients below the upper mixed layer

There were strong positive relationships between salinity and nitrate, silicate, and phosphate. Nitrate, silicate, and phosphate concentrations increased with depth and salinity. Maximum concentrations below the permanent halocline (200-250 m, 32.5 to 33.8 psu) were 40-48 μmole l^{-1} nitrate, 125-150 μmole l^{-1} silicate, and 3.5-3.8 μmole l^{-1} phosphate. The coefficient of determination, r^2, was calculated to determine the degree of linear association between the various nutrients and salinity. The significance of the regressions was tested using an analysis of variance procedure. These relationships were examined using data from depths greater than 75 m, thereby eliminating the upper portion of the water column where biological processes influenced the nutrient concentrations most strongly. The relationships were also examined for depths greater than 150 m across the Seward Line transect.

3.3.1 Nitrate and salinity

The r^2 values were calculated between nitrate and salinity for samples below 75 m and 150 m for each cruise across the Seward Line. The r^2 values for depths greater than 75 m ranged between 0.63 and 0.96 (Table 3.1). In 1998, the relationship was lowest in October ($r^2 = 0.63$) and greatest in April ($r^2 = 0.87$). In 1999, all r^2 values were greater than 0.89, except March 1999 when nitrate data was not evaluated because concentrations > 27 μmole l^{-1} were not properly detected. Overall, the r^2 value for all data points below 75 m in 1998 was 0.56, while in 1999 it was 0.79. An overall r^2 value for 1998-1999 was 0.58.

For samples from depths greater than 150 m, the relationship between nitrate and salinity both strengthened and weakened with the deeper samples. The relationship strengthened with depth in March and April 1998 and April, May, and December 1999. The relationship weakened slightly in May and December 1998 and August 1999. However, the relationship weakened notably in July 1998 and October 1998 and October 1999. The strength of the annual r^2 values at > 75 m and > 150 m remained the same in 1998 but decreased in 1999. The overall r^2 value also decreased with the deeper data set.

There was a stronger, more stable relationship between nitrate and salinity in 1999 than in 1998 for both depth ranges. Both years showed a general decrease in the r^2 values as the year progressed with higher values in the spring and lower values in the fall and winter. The regressions for each month, both years individually, and both years combined for both depth ranges were significant to the 0.0005 level, except October 1998, which was significant to the 0.001 level.

Table 3.1 Coefficient of determination, r^2, between nitrate and salinity at all stations for depths greater than 75 m and 150 m along the Seward Line for March 1998 – December 1999, with the number of samples analyzed in parentheses.

	>75m (n)	>150m (n)
Mar-98	0.84 (69)	0.91 (40)
Apr-98	0.87 (58)	0.94 (33)
May-98	0.77 (100)	0.74 (57)
Jul-98	0.83 (82)	0.60 (48)
Oct-98	0.63 (62)	0.31 (32) *
Dec-98	0.77 (88)	0.76 (60)
Mar-99	---	---
Apr-99	0.96 (86)	0.97 (54)
May-99	0.89 (101)	0.90 (62)
Aug-99	0.96 (82)	0.94 (49)
Oct-99	0.93 (71)	0.85 (41)
Dec-99	0.89 (95)	0.91 (54)
1998 r^2	0.56 (460)	0.56 (272)
1999 r^2	0.79 (435)	0.74 (261)
1998 – 1999 r^2	0.58 (895)	0.53 (533)

* significant to 0.001 level

3.3.1.1 Relationship between salinity and nitrate over the inner shelf

The relationship between nitrate and salinity over the inner shelf (GAK 1 through GAK 3) for samples below 100 m was also evaluated by calculating r^2 values for each cruise (Table 3.2). March 1998 and 1999 yielded the weakest relationships with r^2 values of 0.20 and 0.06 respectively. April and December 1998 relationships were also relatively weak with r^2 values of 0.44 and 0.45. The remainder of the months had r^2 values greater than 0.66. The strongest relationships were in July and October 1998 and April, August, and October 1999. The 1998 r^2 value for depths below 100 m was 0.43 and the r^2 value for 1999 was 0.63. The r^2 value including both years was 0.34. Overall the relationship was stronger and less variable in 1999 than in 1998.

The regressions for each month were significant to the 0.05 level, except that for March 1999, which was not significant. The slopes of the regressions for the twelve sample periods over the two year data set were found to be significantly different ($p \leq 0.05$) from each other indicating that the bottom waters over the inner shelf throughout these two years did not originate from the same source waters. They may have multiple sources or were modified differently.

Table 3.2 Coefficient of determination, r^2, between nitrate and salinity at stations GAK 1 through GAK 3 for depths greater than 100 m for March 1998 – December 1999, with the number of samples analyzed in parentheses.

	r^2 for depths >100 m
Mar-98	0.20 (22)
Apr-98	0.44 (17)
May-98	0.69 (17)
Jul-98	0.83 (11)
Oct-98	0.90 (10)
Dec-98	0.45 (17)
Mar-99	0.06 (16) ±
Apr-99	0.90 (17)
May-99	0.66 (20)
Aug-99	0.98 (14)
Oct-99	0.97 (14)
Dec-99	0.77 (18)
1998 r^2	0.43 (94)
1999 r^2	0.63 (99)
1998 – 1999 r^2	0.34 (193)

± not significant

3.3.2 Silicate and salinity

The relationship between silicate and salinity for water samples deeper than 75 m had r^2 values ranging from 0.57 to 0.87 (Table 3.3). The r^2 values were lowest in April 1998, December 1998, and December 1999, with r^2 values between 0.57 and 0.59. March 1998, July 1998, October 1998, April 1999 r^2 values were slightly larger, with values between 0.69 and 0.78. The remaining months had r^2 values greater than 0.83. The annual trends in the relationship between silicate and salinity had relatively high r^2 values in March which decreased in April, then rebounded to annual maxima values in May of both years. The mean r^2 value for all data points below 75 m in 1998 was 0.53 while 1999 was 0.75. An overall mean r^2 value for 1998-1999 was 0.62.

Excluding depths shallower than 150 m changed the relationship slightly. The relationship strengthened or remained the same with depth in March, April, and May 1998 and March, May, and December 1999. The relationships weakened very slightly in April 1999, August 1999, and October 1999. The r^2 relationship weakened more notably with depth in July and December 1998 and even more extremely in October 1998. The yearly r^2 values and overall r^2 values for 1998-1999 all decreased with the deeper interval.

As seen in the nitrate data, there was a stronger more stable relationship between silicate and salinity in 1999 compared to 1998. Also, the r^2 values were higher in the spring and lower in the fall and winter. The regressions for each month, both years individually, and both years combined for both depth ranges were significant to the 0.0005 level, except October 1998 which was significant to the 0.05 level.

Table 3.3 Coefficient of determination, r^2, between silicate and salinity at all stations for depths greater than 75 m and 150 m along the Seward Line for March 1998 – December 1999, with the number of samples analyzed in parentheses.

	>75m (n)	**>150m (n)**
Mar-98	0.74 (71)	0.79 (40)
Apr-98	0.57 (59)	0.76 (34)
May-98	0.85 (101)	0.85 (59)
Jul-98	0.71 (82)	0.56 (48)
Oct-98	0.69 (62)	0.13 (32) +
Dec-98	0.57 (88)	0.42 (60)
Mar-99	0.86 (68)	0.87 (41)
Apr-99	0.78 (86)	0.77 (54)
May-99	0.87 (101)	0.92 (61)
Aug-99	0.85 (82)	0.82 (49)
Oct-99	0.83 (71)	0.82 (41)
Dec-99	0.59 (95)	0.60 (54)
1998 r^2	0.53 (463)	0.46 (273)
1999 r^2	0.75 (503)	0.73 (303)
1998 – 1999 r^2	0.62 (966)	0.57 (576)

+ significant to 0.05 level

3.3.3 Phosphate and salinity

The r^2 values between phosphate and salinity for depths greater than 75 m were variable with values for data points deeper than 75 m between 0.40 and 0.91, except for March 1998, which had an extremely low value of 0.16. (Table 3.4). The r^2 values were between 0.40 and 0.70 in April, July, October, December 1998 and April 1999. The remaining months, May 1998 and all of 1999 except April, produced r^2 values greater than 0.80. The overall r^2 values between phosphate and salinity below 75 m were 0.43 in 1998 and 0.73 in 1999. An overall r^2 value for 1998-1999 was 0.56.

The relationship increased or remained unchanged with the deeper depth interval in March, April, May, and October 1998 and May 1999. The relationship decreased slightly in March, April, and December 1999 and more notably in July and December 1998 and August and October 1999. The deeper depth interval produced slightly smaller r^2 values between phosphate and salinity for 1998, 1999, and overall.

As found with nitrate and silicate, the relationship between phosphate and salinity was weaker and more variable throughout 1998, and stronger and more stable throughout 1999. However, the r^2 values generally increased during both years and over the two year period. The regressions for all the data sets were significant to the 0.0005 level for both depth ranges, except in March 1998.

Table 3.4 Coefficient of determination, r^2, between phosphate and salinity at all stations for depths greater than 75 m and 150 m along the Seward Line for March 1998 – December 1999, with the number of samples analyzed in parentheses.

	>75m (n)	**>150m (n)**
Mar-98	0.16 (71) *	0.16 (40) ~
Apr-98	0.42 (57)	0.60 (34)
May-98	0.80 (101)	0.83 (59)
Jul-98	0.55 (82)	0.24 (48)
Oct-98	0.40 (62)	0.46 (32)
Dec-98	0.70 (88)	0.63 (60)
Mar-99	0.81 (68)	0.80 (41)
Apr-99	0.67 (86)	0.64 (54)
May-99	0.91 (101)	0.93 (61)
Aug-99	0.85 (82)	0.77 (49)
Oct-99	0.80 (71)	0.72 (41)
Dec-99	0.84 (95)	0.83 (54)
1998 r^2	0.43 (463)	0.42 (275)
1999 r^2	0.73 (503)	0.72 (303)
1998 – 1999 r^2	0.56 (966)	0.55 (578)

* significant to the 0.001 level

~ significant to the 0.01 level

4. DISCUSSION

4.1 Annual nutrient cycles

4.1.1 Surface drawdown and new production estimates

Nutrient data collected from the Seward Line showed seasonal drawdown and possible limitation by nitrate, silicate, and phosphate in the upper water column. Nutrient drawdown was evident as early as March in the inner shelf, shelf-break, and offshore regions. Integrated nitrate concentrations (0-50 m) were lowest every year over the inner shelf compared to the other regimes. The surface drawdown extended across the shelf by summer and continued into fall. During the fall months, the nutrient drawdown either continued and extended to deeper depths, as measured in 1998, or was subdued as the nutrients were replenished, as occurred in 1999. By December the upper water column was being replenished in nutrients due to winter wind mixing.

Winter wind mixing and stratification due to freshwater discharge were found to strongly influence the supply of nutrients to the euphotic zone. Furthermore, the stability of the upper water column in the spring is believed to largely determine the ability of the phytoplankton community to become established and bloom. Chlorophyll *a* concentrations were higher throughout the spring of 1998, when stratification was stronger, indicating the importance of stability compared to the well mixed, high nutrient water column in 1999.

The decrease in nutrient concentrations throughout the spring and summer months coincided with an increase in phytoplankton biomass. From the mean depth integrated nitrate concentrations within the four shelf regimes for the time periods March-July 1998 and March-August 1999, rough estimates of new production were made (Table 4.1). These calculations assume that March and July/August represented annual maximum and minimum nitrate concentrations and advection/diffusion and other gains and losses in the upper 50 m were insignificant. The highest calculated rates of new production occurred over the inner shelf both years, with a higher rate in 1998 (2.58 mmole m^{-2} day^{-1}) than

1999 (1.89 mmole m^{-2} day^{-1}). These estimates are minimum values considering this shelf experiences advection and diffusion through various mechanisms including along-shelf and cross-shelf transport, coastal inputs, and storm events. It is also possible that nitrate utilization occurred over shorter time periods than evaluated here.

Table 4.1 New production estimates calculated from changes in 0-50 m integrated nitrate concentrations within the four shelf regimes during the time periods March-July 1998 and March-August 1999. Units are mmole nitrate m^{-2} day^{-1}.

	1998	**1999**
Inner shelf	2.58	1.89
Middle shelf	2.00	1.36
Shelf-break	0.94	1.31
Oceanic	1.63	0.90

Other estimates from the Gulf of Alaska include depth integrated nitrate uptake from Ocean Station Papa for May and September, which was 45 mg nitrate m^{-2} day^{-1}, or 3.21 mmole nitrate m^{-2} day^{-1} (WHEELER and KOKKINAKIS, 1990). This estimate is larger than any made for our study region. This further suggests that these rough calculations may have underestimated new production rates. However, another annual new production estimate from Ocean Station Papa, calculated by Welschmeyer et al. (1993), was 480 mmole nitrate m^{-2} y^{-1}, which is similar to the annual estimate from the oceanic regime of the Seward Line (461 mmole nitrate m^{-2} y^{-1}). Therefore, the oceanic regime from our study region could potentially have new production similar to that of GOA gyre waters.

4.1.2 Onshore flux of nutrients onto the northern GOA shelf

The flux of nutrient-laden waters onto the northern GOA shelf enriched the shelf waters. The seasonal onshore flux of nutrient-rich bottom waters onto the shelf created a nutrient reservoir over the inner and middle shelf. This reservoir acted as a nutrient source and was eventually distributed all through the water column during the winter months. Without this onshore flux and generation of a nutrient reservoir followed by storm events and winter mixing, the euphotic zone would most likely not be able to support such a productive ecosystem.

The following calculations were made in an effort to estimate the amount of nitrate introduced onto the shelf during the summer onshore flux, which could subsequently be mixed into the upper water column. The area of the inner shelf, ~50 km wide, from the tip of the Kenai Peninsula to Yakutat, is 33,150 km^2. The area of the inner shelf deeper than ~150 m is 12,282 km^2, ~37% of the total area. The volume below 150 m, with an average depth of 75 m, is 921 km^3. With an average nitrate concentration of ~20 mmole m^{-3} in December, this reservoir contains ~2.58×10^5 kg nitrate nitrogen. This reservoir is replenished in the summertime by the onshore flux of waters deeper than ~150 m. This layer is ~50 m thick and we assume it flows onshore at ~2.0 cm sec^{-1} (estimated from the onshore displacement of the sigma-t = 26.0 kg m^{-3} isopycnal intersection with bottom) (WEINGARTNER, personal communication). The length of the shelf 50 km offshore and deeper than 150 m is ~421 km. Therefore, ~0.07 Sv flows onto the northern GOA shelf below 150 m. With nitrate concentrations ~35 mmole m^{-3} in this deep layer, and the flux lasting two months with a volume of ~3.64×10^{11} m^3, ~1.78×10^8 kg nitrate nitrogen are brought onto the shelf during the summer onshore flux.

For comparison, similar calculations were made for Hinchinbrook Canyon, to determine the potential importance of deep canyons. Hinchinbrook Canyon is ~10 km wide and if we assume a quasi-continuous flow up the canyon of a deep layer, ~50 m thick, flowing at ~3 cm sec^{-1} (approximated from average cross-shelf flows) (WEINGARTNER, personal communication). Therefore, approximately 0.015 Sv flows up the canyon. This mass of water over the course of a year with ~35 mmole nitrate m^{-3} would introduce ~2.28×10^8 kg nitrate nitrogen onto the inner shelf. Therefore, the small yet 'continuous' flow up Hinchinbrook Canyon introduces ~20% more nitrate onto the shelf than the seasonal flux onto the shelf. This simple and speculative first order calculation suggests that deep canyons, such as Hinchinbrook Canyon, could play an important role in supplying nutrients to the shelf.

Calculations were made comparing the rate of nitrate diffused into the upper water column from depth versus the rate of nitrate advected to the inner shelf through the surface Ekman layer under December conditions. Nitrate diffusion rates were calculated for the inner shelf by splitting the water column into three layers: the upper layer (0-50 m), a middle layer (50-150 m), and a bottom layer (150 m to the bottom). Mean nitrate concentrations from stations GAK 1-3 in December 1998 and 1999 over these depth ranges were averaged over the two years. Diffusivities of 0.005 and 0.060 $m^2\ sec^{-1}$ were used to determine a range in diffusion rates (WILLIAMS and WEINGARTNER, 1999). Nitrate diffusion rates from the middle layer to the upper layer ranged from 1.1×10^{-4} to 1.4×10^{-3} mmole nitrate $m^{-2}\ sec^{-1}$. Diffusion rates from the bottom layer to the middle layer were similar, with a range of 3.3×10^{-4} to 3.9×10^{-3} mmole nitrate $m^{-2}\ sec^{-1}$. Using the weaker diffusivity estimate for nitrate diffusion from the middle layer to the upper layer within the frontal zone, which is approximately 10 km wide, the rate of nitrate diffusion was calculated to be 1.14 mmole nitrate $m^{-1}\ sec^{-1}$ within the inner shelf under early winter conditions.

The amount of nitrate fluxed onto the inner shelf via surface Ekman transport was estimated using conditions found during the previous winter (along shore wind speed averaging 8 m sec^{-1}, thickness of the Ekman layer approximately 30 m, and an offshore gradient of 3 mmole nitrate m^{-3} measured over a distance of 150 km). Under these conditions, the onshore advection of nitrate into the inner shelf was calculated to be 1.00×10^{-3} mmole nitrate $m^{-1}\ sec^{-1}$. From these first order calculations, the role of vertical diffusion of nitrate into the upper layer during early winter appears to be much larger than that of onshore advection via surface Ekman transport. This further supports the importance of the reservoir created over the inner shelf during the seasonal onshore flux as a nutrient source to the coastal waters. However, as mentioned earlier, the total water column inventory of nitrate and silicate in December 1998 was much lower than what was measured the following March 1999. Therefore, there are nutrient sources in addition to vertical mixing, such as along-shelf advection within the Alaska Coastal Current, which exports water from Prince William Sound.

4.2 Interannual features and dynamics

The two years studied, 1998 and 1999, showed large differences in the physical, chemical, and biological distributions across the Seward Line. These years were embedded within different phases of ENSO and the PDO (MANTUA, 1999; NOAA, 2001). As a result, the climatic and physical forcings were different between the years. Early spring 1998 had greater stratification, because of freshening, than spring 1999. Consequently, the entire water column across the shelf in spring 1998 was warmer, fresher, and lower in nitrate. On the other hand, the water column was very well mixed with higher nitrate concentrations in the spring of 1999.

The summer months had interannual differences in the physical features and nutrient distributions, due either to interannual variability or differing sampling times. The upper ~50 m across the transect were more highly depleted in nitrate in 1998 compared to 1999. The bottom onshore flux resulted in maximum nutrient concentrations earlier in 1998 (May over the middle shelf and seaward, July over the inner shelf) than 1999 (August across the transect) with bottom nitrate concentrations consistently higher in 1999. The results for fall and early winter months displayed more extensive surface drawdown of nutrients in 1998 compared to an earlier, more active replenishment of nutrients in the upper water column in fall 1999, with depth integrated nutrient concentrations notably higher in December 1999 than December 1998. This indicates that either enrichment processes had increased or biological intake had decreased in 1999 to drive the inventory of the water column higher.

4.3 Attributes of mesoscale features across the Seward Line

4.3.1 Inner Shelf Regime

The inner shelf regime is a very dynamic region of the shelf that encompasses the Alaska Coastal Current and is directly affected by coastal features. The physical properties of the inner shelf are driven primarily by salinity, therefore freshwater inputs play a large role in the physical structure of the inner shelf. The ACC, which is driven by freshwater inputs, varies in speed (with maximum speeds in the fall) and in vertical and horizontal extent depending on seasonal and climatic conditions. Therefore, along-shelf advection of terrestrial inputs within the ACC throughout the year clearly modifies the nutrient distributions over this region of the shelf. The inner shelf may also be influenced by waters within the ACC which flow through and out of Prince William Sound. These waters could introduce estuarine nutrients or export phytoplankton biomass onto the shelf, initializing or supporting a bloom over the inner shelf.

This two-year data set showed that the inner shelf experienced a well-mixed water column throughout winter and spring, followed by a relatively stable, or stratified, water column throughout summer and fall. During the summer months the water column had very fresh, warm, nutrient-poor water at the surface within the ACC accompanied by a dense nutrient-rich bottom layer created by the onshore flux. The nutrients at depth were eventually mixed throughout the water column during the winter months, replenishing the surface waters. Throughout an annual cycle, the inner shelf experienced two extremely distinct conditions between seasons, with a thoroughly mixed water column in winter and spring due to storm mixing and a stable water column in summer due to stratification.

The inner shelf appears to be one of the more productive regions of the shelf, with relatively high phytoplankton biomass and the highest new production rates, as indicated by the disappearance of nitrate. This region of the shelf has two primary nutrient sources: freshwater or coastal inputs within the ACC and the nutrient-rich bottom waters moved onto the shelf during the summer months, which are subsequently mixed throughout the water column. This region also experiences earlier, stronger degrees of stratification due to freshwater inputs. The nutrient sources and level of stratification over the inner shelf may explain the high chlorophyll *a* concentrations and new production rates.

At GAK 1, near the mouth of Resurrection Bay, the nitrate and silicate concentrations decreased throughout spring, summer, and fall of both years (except for uniquely high silicate concentrations in April 1998). The upper 50 m at GAK 1 were not replenished until December of both years. Throughout the two years, the inner shelf regime usually had the lowest depth integrated nitrate concentrations compared to the other shelf regimes. At the same time, relatively high surface and depth integrated chlorophyll *a* concentrations were found at GAK 1. A spring phytoplankton bloom occurred in April of both years. This increase in chlorophyll biomass, when compared to the rest of the shelf, may be enhanced by higher chlorophyll waters flowing out of Prince William Sound. The phytoplankton biomass then decreased throughout the remainder of the year to minimum values in October and December.

The nutrient and phytoplankton trends changed farther offshore at GAK 4. The depth integrated nitrate and silicate concentrations did not decrease throughout the spring months, but instead peaked in April 1998 and May 1999. Furthermore, there was replenishment of nitrate and silicate in the upper 50 m by October 1999. The chlorophyll *a* concentrations did not peak until May 1998 and August 1999, with concentrations considerably lower than measured at GAK 1. Therefore, even though these stations were chosen to characterize the inner shelf, GAK 4 was far enough offshore to be influenced differently by the ACC in addition to middle shelf features.

4.3.2 Middle Shelf Regime

The middle shelf regime is the shallowest region of the Seward Line, and is characterized by relatively slow shelf flow complicated by occasional eddy activity. This region of the shelf did not undergo complete vertical mixing during the winter months as did the inner shelf. Instead, high salinity, high nutrient bottom water was evident for most of the year. Depth integrated nitrate concentrations at GAK 6 increased dramatically during spring 1998, although the concentrations were not as large and remained relatively constant during the spring of 1999. May 1998 and 1999 had especially high nitrate concentrations (high silicate in 1999) in the upper water column over the middle shelf, which may have been due to eddy activity. The upper water column became stratified during the summer and fall months and experienced notable nutrient drawdown, which was more extensive in 1998. By December, the upper water column was being replenished, with depth integrated nutrient concentrations being clearly higher in 1999.

The spring phytoplankton bloom over the middle shelf appeared in May of both years, with high surface and depth integrated chlorophyll *a* concentrations persisting though July/August. The spring phytoplankton blooms in 1998 and 1999 corresponded with the appearance of extraordinarily high depth integrated nitrate concentrations, suggesting the importance of enrichment of the upper water column, perhaps by eddies, to heightened phytoplankton activity over the middle shelf. Estimates of new production for the middle shelf were higher than those for the shelf-break and oceanic regimes, yet lower than the inner shelf estimates. These relatively high estimates were probably due to the rapid drawdown of nitrate during the May spring bloom period, followed by low concentrations extending throughout the summer months. This region also had relatively high concentrations of marine birds and mammals, further exemplifying its high biological productivity (DAY, personal communication).

4.3.3 Shelf-Break Regime

The shelf-break area is a unique part of the shelf affected by various shelf-break dynamics including frontal systems, shear, and onshore advection of the slope waters. Shelf-break fronts are commonly recognized as regions of higher biological productivity, since they lie between well mixed shelf waters and stratified offshore waters where nutrients are brought to the surface by turbulence or tidal mixing, leading to conditions suitable to phytoplankton production (LALLI and PARSONS, 1993).

This region of the shelf had more structure than was found inshore, since the water column retained some vertical stratification throughout the winter and spring months. During the spring months at GAK 9, the depth integrated nitrate and silicate concentrations increased in 1998 but decreased in 1999. These increasing nutrient trends in spring 1998 were accompanied by slowly increasing chlorophyll *a* concentrations which eventually reached maximum concentrations in July. However, in spring 1999, the phytoplankton biomass reached peak concentrations in May coinciding with the reduction in nutrient concentrations.

These spring conditions were followed by a general decrease in depth integrated nitrate and silicate concentrations, except nitrate concentrations in August 1999 which approached early spring concentrations. This increase was due to the onshore (upward) flux of nitrate-rich waters, which dramatically enhanced nitrate concentrations throughout the water column, even as shallow as 25-30 m. The onshore flux in 1998 was not as conspicuous and reached maximum bottom concentrations earlier in the year, in May. The surface chlorophyll *a* concentration at GAK 9 in July 1998 was the highest measured along the Seward Line throughout the two years. The chlorophyll *a* concentrations in August 1999, which were less than half the concentrations measured in July, continued to decrease following the maximum concentrations in May.

In October, the depth integrated nitrate and silicate concentrations had decreased and there were annual minimum chlorophyll *a* concentrations. By December of both years, the nutrient concentrations in the upper 50 m were being replenished and in 1999 there was a small rebound in phytoplankton biomass. Ammonium concentrations throughout the water column in this region were notably high in August 1999 and December of both years.

The new production estimates for the shelf-break were relatively low compared to the other regions of the shelf in both years. The estimates for this region were underestimated since they did not take into account processes such as advection and/or diffusion of nitrate-rich slope waters into the upper water column. The shelf-break had relatively high chlorophyll *a* concentrations along with the highest overall densities of seabirds and high marine mammals, suggesting it may be one of the more productive regions of the shelf (DAY, personal communication).

4.3.4 Oceanic Regime

The oceanic regime is farthest offshore, encompassing the slope waters that are influenced primarily by physical features, including the Alaskan Stream and GOA gyre. This regime did not experience as much variability in the nutrient distributions or physical properties as measured in the other shelf regimes. Winter mixing was found to affect mostly the upper 25-100 m of the water column. The depth integrated nitrate and silicate concentrations at GAK 13 decreased throughout the spring months both years, while the increase of chlorophyll *a* concentrations indicated phytoplankton activity as early as March 1998 and reached a maximum in May 1998. The depth integrated nutrient concentrations continued to decrease into summer 1998. However, there was an increase in nitrate in August 1999, as seen at GAK 9, due to the upward flux of seasonally nitrate-rich bottom waters. In October, the depth integrated nitrate concentrations either remained the same (1998) or decreased (1999) while silicate increased. Finally in December, the nutrients were generally being replenished in the upper 50 m.

Chlorophyll *a* concentrations offshore were lower than those measured in the shoreward regimes. New production estimates for this region were also relatively low compared to the other regimes. Results from Ocean Station Papa suggest chlorophyll concentrations in the GOA are low due to grazing pressure and/or iron limitation, and primary productivity is derived mainly from regenerated production (HARRISON et al., 1999). The Seward Line oceanic regime is potentially very similar to the open Gulf; therefore, these factors may also be affecting the phytoplankton biomass.

4.4 Major nutrient relationships with salinity

There was a positive relationship between salinity and nitrate, silicate, and phosphate in the data collected along the Seward Line. Nitrate, silicate, and phosphate concentrations increased with depth and salinity, reaching maximum values offshore of the shelf-break within the oceanic regime below the permanent halocline. Therefore, it can be concluded that nutrient-rich waters beyond the shelf-break are the primary nutrient source to the shelf. However, the occurrence of weak relationships suggest multiple nutrient source waters or that biological effects extend deeper than 75 and 150 m. Since large concentrations of regenerated forms of nutrients were not commonly found, either in the mixed layer or subpycnocline layer, nutrient remineralization is probably a secondary source of nutrients supporting productivity.

When considering the data deeper than 75 m, the r^2 relationships were overall weaker and much more variable in 1998 than 1999. This difference could be due to the sample condition when processed, since the samples in 1998 were processed after being frozen and transported, while the samples in 1999 were run fresh onboard within hours of collection. On the other hand, we have no evidence that the frozen samples were in error, so this distinction could be due to interannual differences between 1998 and 1999, which were also evident in the temperature and salinity profiles.

When considering the depth intervals > 150 m, the spring months in 1998 generally had a stable or stronger r^2 relationship between nitrate, silicate, and phosphate and salinity with increasing depth. However, the r^2 relationships in July, October, and December 1998 generally weakened with depth. The data collected in 1999 showed a similar, yet less obvious pattern. The r^2 relationships generally increased or changed only slightly in March, April, and May 1999 with increasing depth, while August and October values decreased and December remained stable. Overall, the r^2 relationships between nitrate, silicate, and phosphate and salinity increased with depth in the spring months, while they became weaker during the summer and fall months. This could have been due to biological processes such as denitrification in the bottom waters, but more data are needed to clarify these changing relationships.

The nitrate-salinity results from over the inner shelf, GAK 1 through GAK 3, produced a positive linear r^2 relationship for depths below 100 m, with an overall value of 0.34, which was significant to the 0.0005 level. This relatively weak relationship overall and between months suggest that processes such as advection and/or mixing are involved. This also indicates that the bottom waters over the inner shelf have multiple source waters or they were modified differently throughout the sampling period. A future goal is to correlate this data with salinity information from GAK 1 for the past 30 years to hindcast nitrate concentrations over the inner shelf (Royer, personal communication). The GAK 1 database is important in this regard, because it will allow for estimating the amount of nitrate present in the bottom waters over the inner shelf that could have been available to the biologically active surface waters.

5. CONCLUSIONS

The Gulf of Alaska is a dynamic shelf that supports a biologically productive ecosystem. The major nutrient distributions across the shelf showed the general profile of increasing nitrate, silicate, and phosphate concentrations with depth and salinity. These nutrients reached maximum concentrations in the oceanic waters offshore of the shelf-break below the permanent halocline. The positive relationships found between these major nutrients and salinity indicate that the slope waters are the primary nutrient source to the shelf waters. The nutrient-rich slope waters are delivered to the shelf by way of a seasonal onshore flux during the summer months, when the downwelling regime is weakest or potentially upwelling. The productivity of the shelf is believed to rely heavily on this summer onshore flux which delivers dense, nutrient-rich water to the relatively deep inner shelf, which acts as a basin where these waters remain until winter. During the winter months, this nutrient reservoir is mixed throughout the water column by the winds, supplying nutrients to the upper water column. This annual evolution may be crucial to biological production over this region of the northern GOA shelf.

The presence of bathymetric features, such as Hinchinbrook Canyon, may play very important roles in supplying nutrients to the shelf waters. First order calculations suggested that flow through this canyon alone provided more nutrients to the shelf throughout a year than the seasonal onshore flux. This potentially large nutrient source needs to be sampled more fully and a more thorough analysis should be undertaken.

The upper water column undergoes an annual cycle of nutrient drawdown and replenishment in response to the physical and biological conditions. Throughout the winter months, the nutrients are evenly distributed throughout the water column through vertical wind mixing. The nutrients are then available for the onset of a spring bloom which reduces nutrient concentrations. As the year progresses into summer and fall, the nutrients are drawn down to limiting or near limiting conditions in the surface waters. At this time, the upper water column is strongly stratified due to warmer, fresher surface waters and provides a stable, yet nutrient-poor euphotic zone for the phytoplankton community. As fall progresses into winter, the winds strengthen and the upper water column begins to be replenished. Late winter wind mixing events, when the freshwater inputs and water temperatures have decreased, are vital to the replenishment of the nutrients to the upper water column. During each annual cycle, nutrient concentrations in the upper water column are depressed and reach limiting or near limiting conditions; nevertheless, winter wind mixing replenishes the surface waters by distributing the higher nutrient concentrations at depth throughout the water column.

Estimates of new production rates were first order approximations derived from changes in upper water column nitrate concentrations. The calculations showed that new production was generally higher in 1998. Both 1998 and 1999 had the highest rates in the inner shelf with the second highest rates in the middle shelf. These estimates are lower than estimates from the open GOA, but these approximations ignore processes such as advection/diffusion. In addition, these estimates were calculated over several month periods when the real uptake may have been actually much more rapid. Therefore, it is believed that these calculations underestimated new production rates.

This two year data set showed a large degree of interannual variability in the physical, chemical, and biological properties across the shelf. The water column in the winter and spring of 1997-98 had warmer, fresher waters along with more stability, which combined with weaker winds resulted in reduced vertical mixing. On the other hand, the water column in the winter and spring of 1998-99 was very well mixed with higher nitrate concentrations throughout the water column. The seasonal onshore flux at depth produced maximum bottom nitrate concentrations earlier in 1998 (May/July) than 1999 (August). This was much more intense and conspicuous in 1999 with maximum nitrate concentrations measured below 50 m across the shelf. Nutrient drawdown in the upper water column was more extensive in the summer and fall of 1998. In October 1999, the surface waters were being replenished, whereas in October 1998 nutrient utilization continued. By December both years, the upper water column was being replenished, but nutrient concentrations were considerably higher in 1999 compared to 1998.

This interannual variability may be related to climatic variability of the El Nino/Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO). Warm phases of the PDO have been found to enhance biological productivity in Alaskan waters and the most recent warm phase lasted from 1977 through 1999 (MANTUA, 1999). This warm phase of the PDO was accompanied by a strong El Nino in 1997-1998. These climatic and oceanographic conditions may help clarify or explain the differences in the physical and chemical properties measured in 1998 and 1999 and the higher chlorophyll *a* concentrations and new production estimates in 1998. A better understanding of these climatic phases and their effects on physical properties of the GOA will allow for better interpretations of their relationship to nutrient distributions and ultimately biological productivity.

The four shelf regimes have mesoscale features that contribute to their characteristic seasonal patterns of nutrient content and productivity. 1) The inner shelf represents the typical coastal regime which undergoes thorough winter mixing and summer stratification. Stratification over the inner shelf is driven primarily by freshwater inputs and appears earlier than in the other regimes. This region is characterized by comparatively low depth integrated nutrient concentrations, relatively high chlorophyll levels, and the highest new production estimates. This regime has numerous nutrient sources including coastal inputs, along shore advection within the ACC, and the nutrient reservoir created at depth during the summer onshore flux. 2) The middle shelf is the shallowest section of the transect and features relatively weak, variable shelf flow with occasional eddy activity. This region is characterized by relatively high biological productivity and high new production estimates. The productivity of this region may be driven partly by the occurrence of eddies. 3) The shelf-break regime is an especially productive region of the shelf which features high chlorophyll *a* concentrations, high bird densities, and high marine mammal counts. The biological productivity of this region is supported by physical processes associated with the shelf-break which enhance primary productivity. Finally, 4) the oceanic regime is characterized by oceanic waters within the Alaskan Stream, which are relatively stable and lower in biological productivity compared to the shelf waters. This region did show seasonality in the nutrient concentrations and phytoplankton biomass distinguishing this region from open ocean waters. Nevertheless, the phytoplankton biomass of these waters may be limited by processes discovered in the open GOA, such as micro-nutrient limitation or grazing pressure.

The source and movement of the major nutrients onto the shelf is not completely understood. However, the physical, chemical, and biological data collected from nearby transects and additional years of data will help to clarify the features and dynamics within this region of the northern GOA shelf. For instance, the significance of transport of nutrient-rich slope waters through submarine canyons such as Hinchinbrook Canyon to the shelf remains uncertain. It is also undetermined if the waters flowing out of Prince William Sound influence the nutrient distributions over the inner shelf or if they export phytoplankton biomass out onto the shelf. With the continued support of the Global Ocean Ecosystem Dynamics (GLOBEC) Gulf of Alaska Long Time Series Observation Program (LTOP), we will have a much larger data set to analyze. Hopefully, we will be able to better generalize the annual nutrient trends across the shelf, improving our understanding of the nutrient sources and dynamics that support this biologically productive shelf ecosystem.

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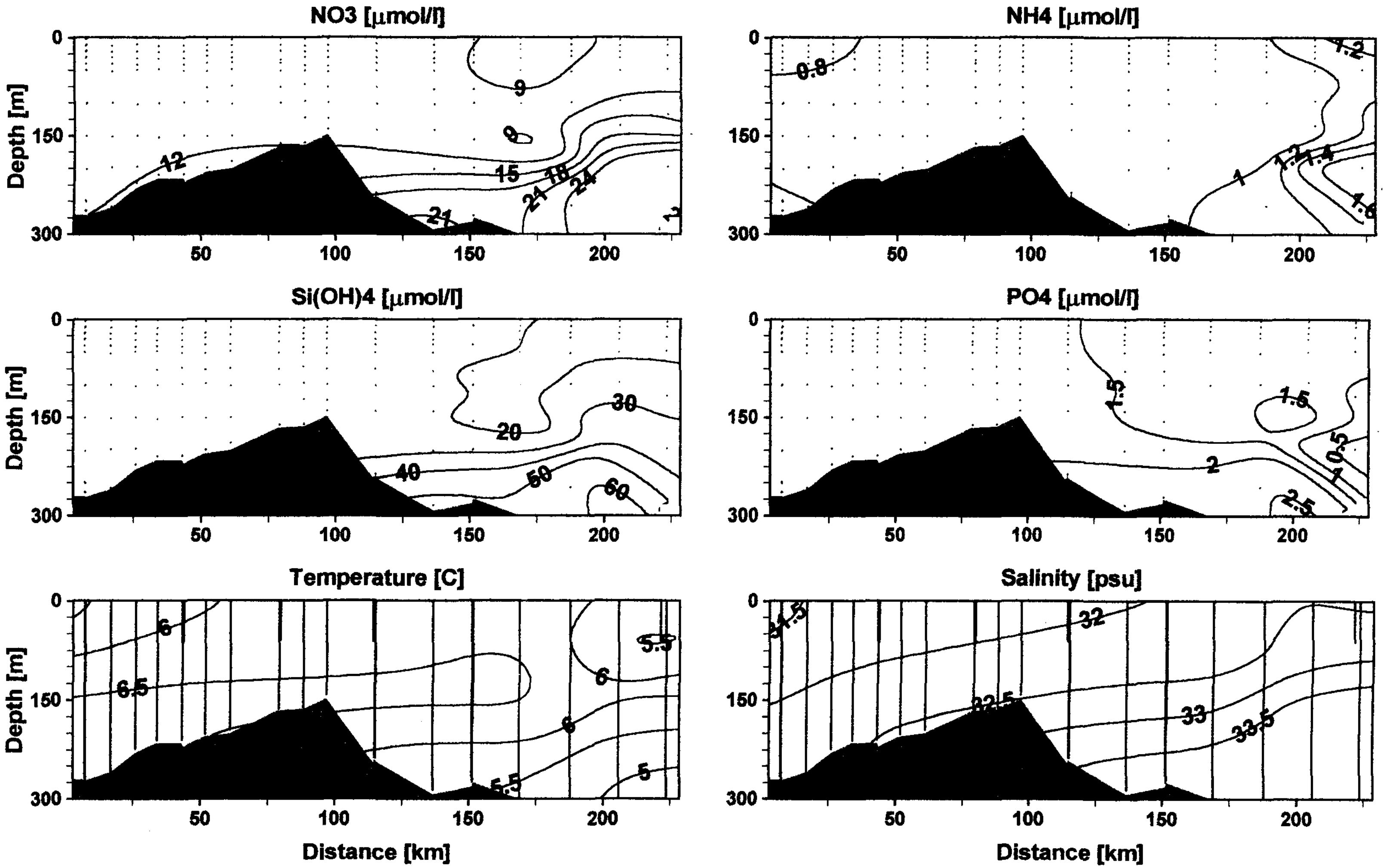
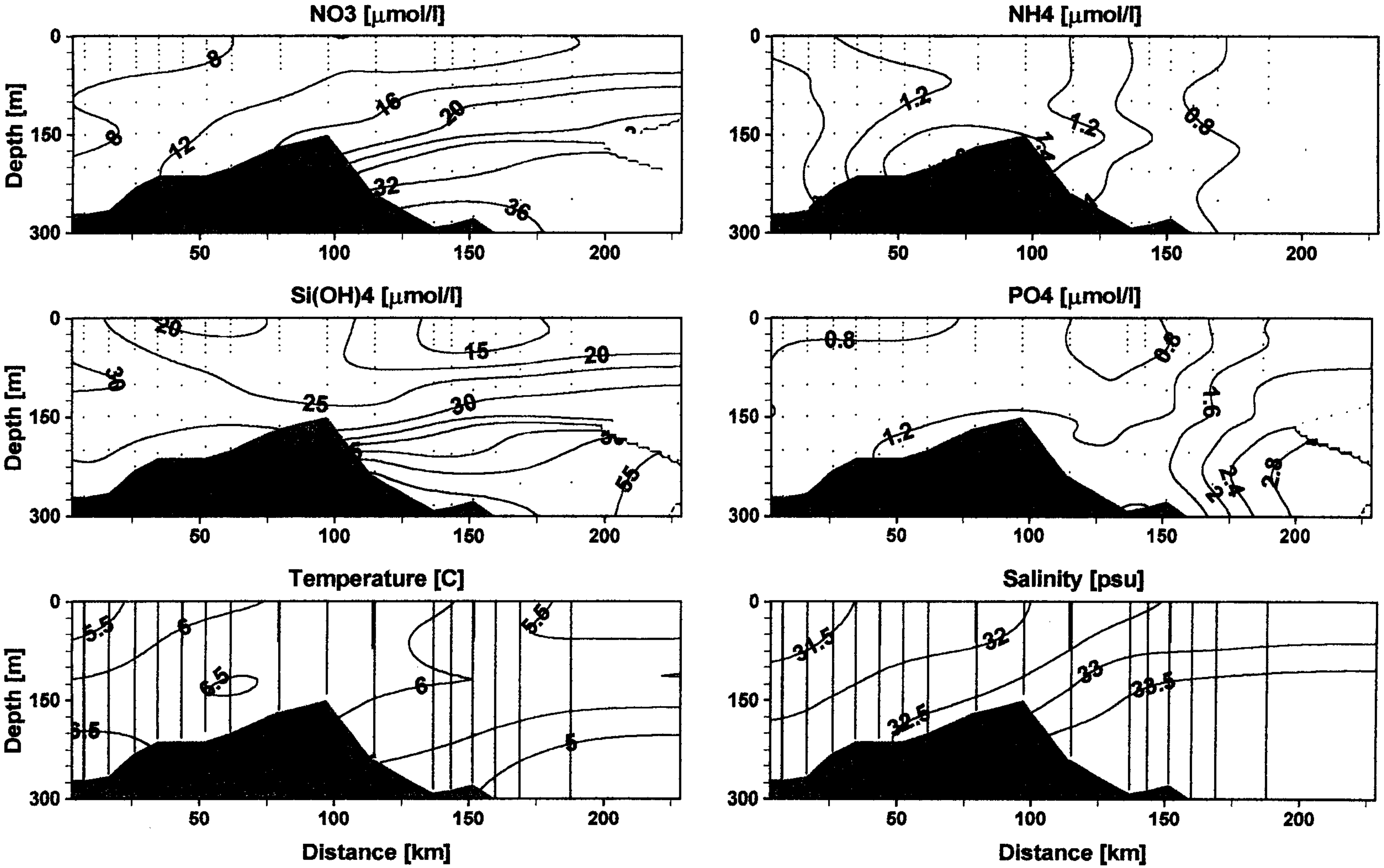
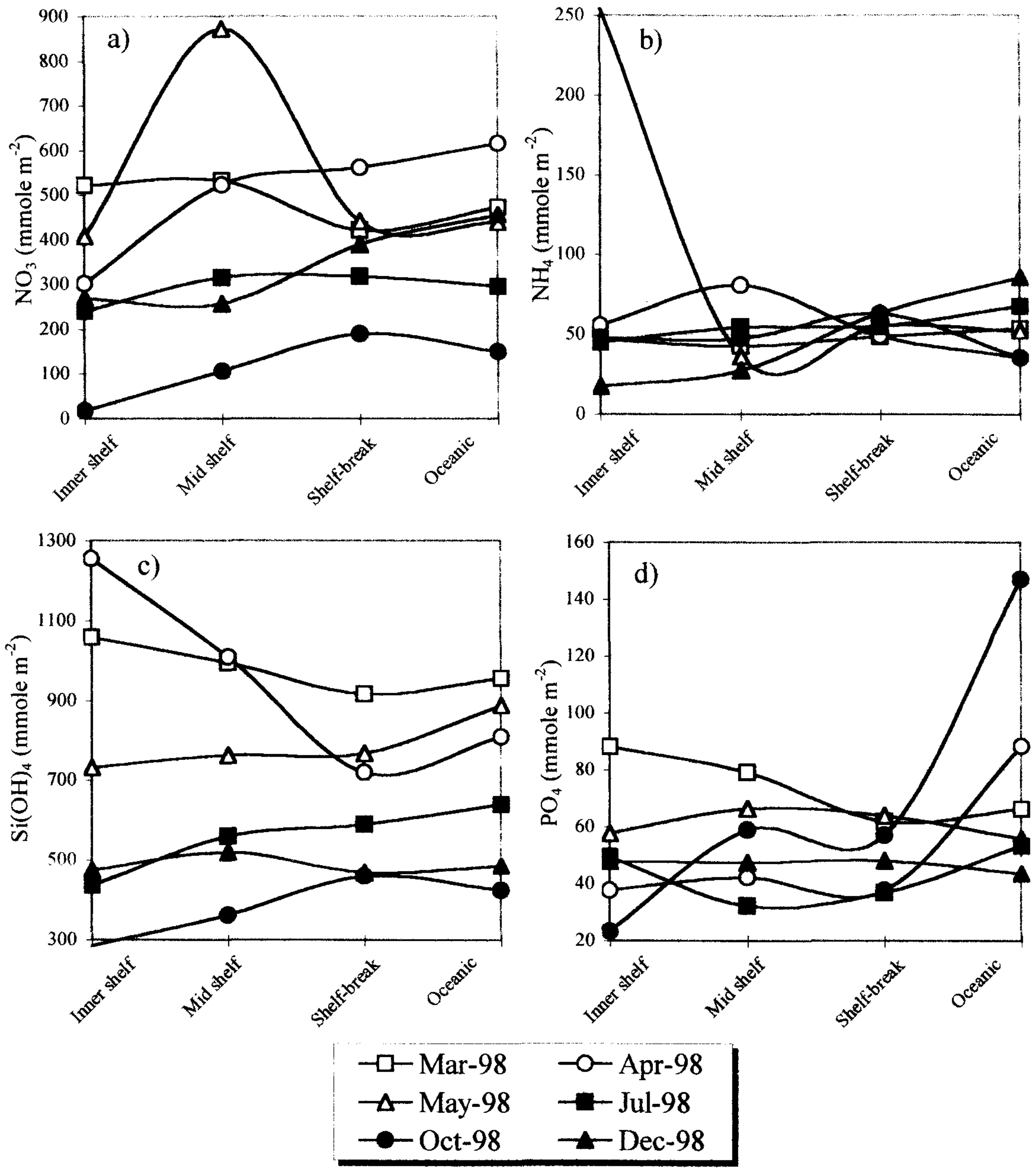
7. APPENDIX 1: SUPPLEMENTARY 1998 FIGURES



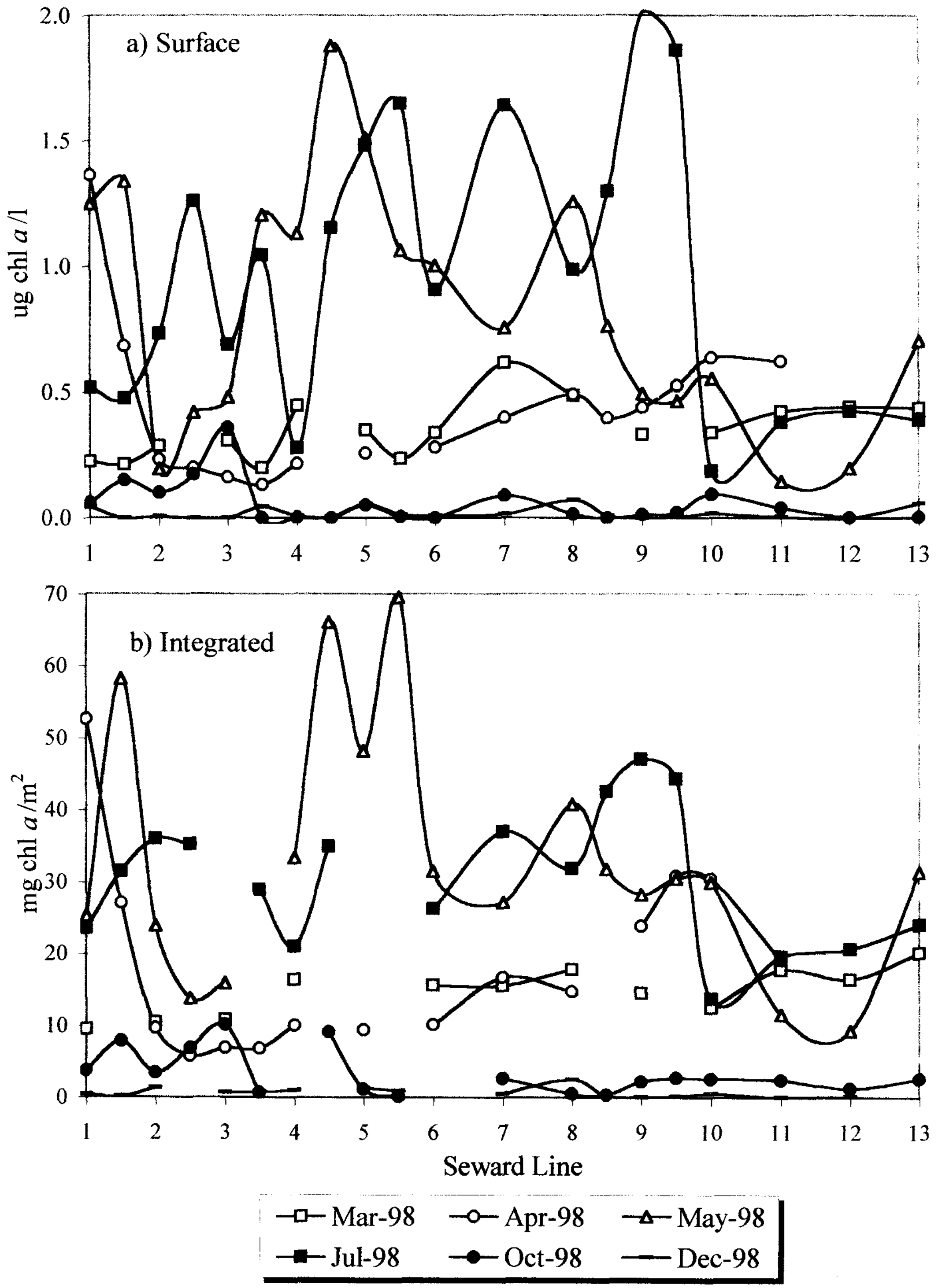
Appendix 1.1 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 8-13 March 1998. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).



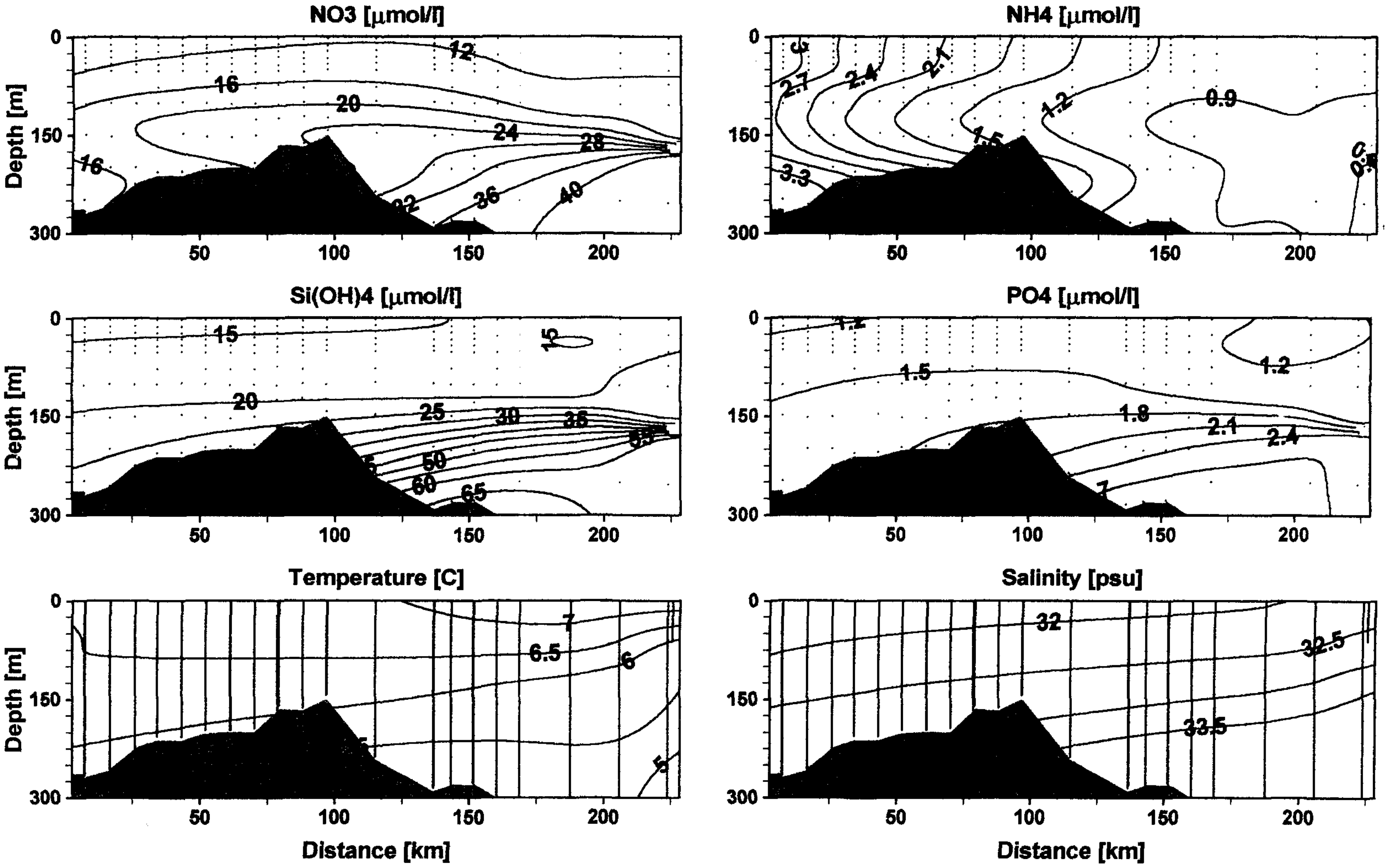
Appendix 1.2 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 1-5 April 1998. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).



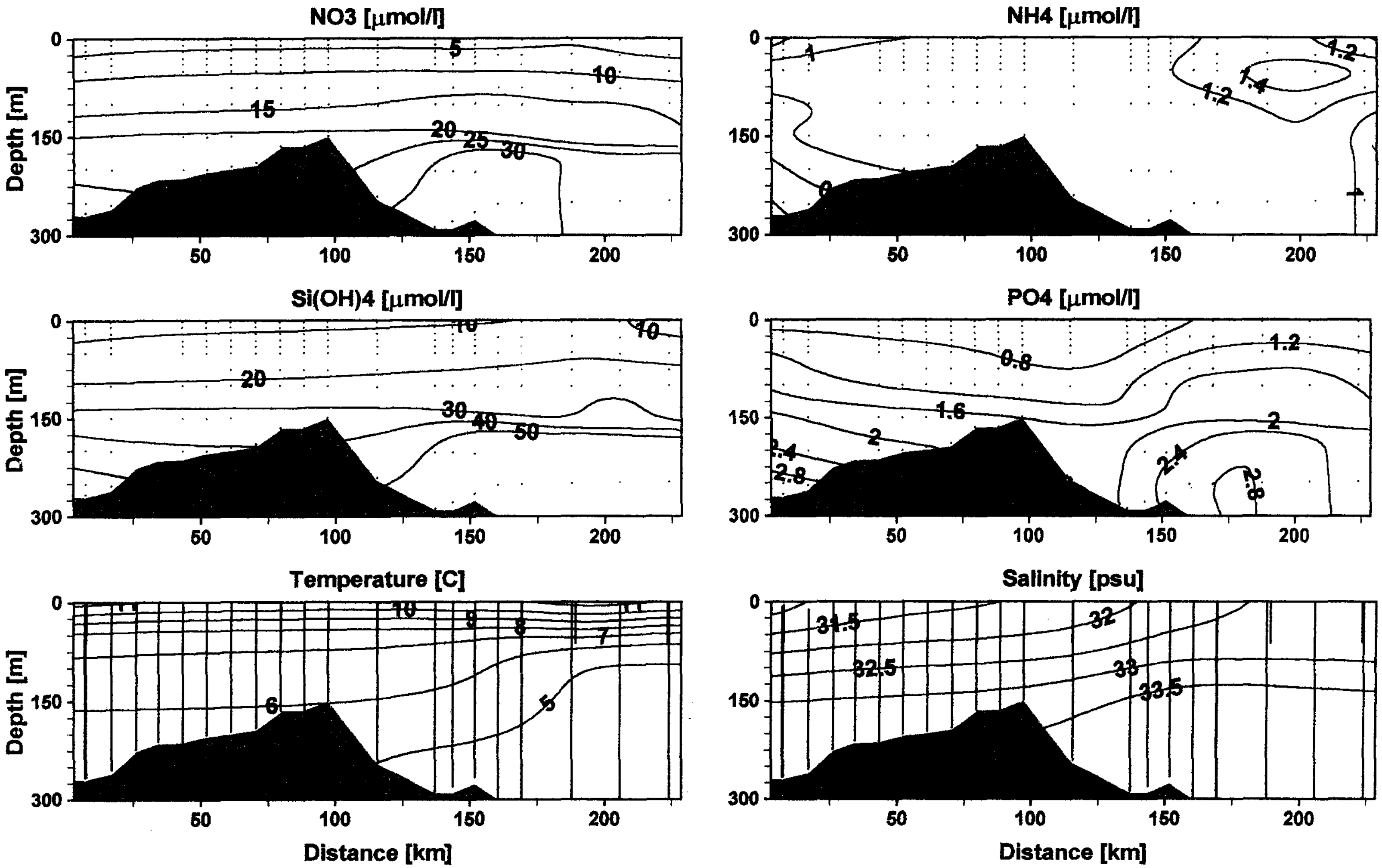
Appendix 1.3 Mean integrated (0-50 m) a) nitrate, b) ammonium, c) silicate, and d) phosphate concentrations across the Seward Line within the four shelf regimes, March through December 1998. Concentrations in mmole m^{-2}.



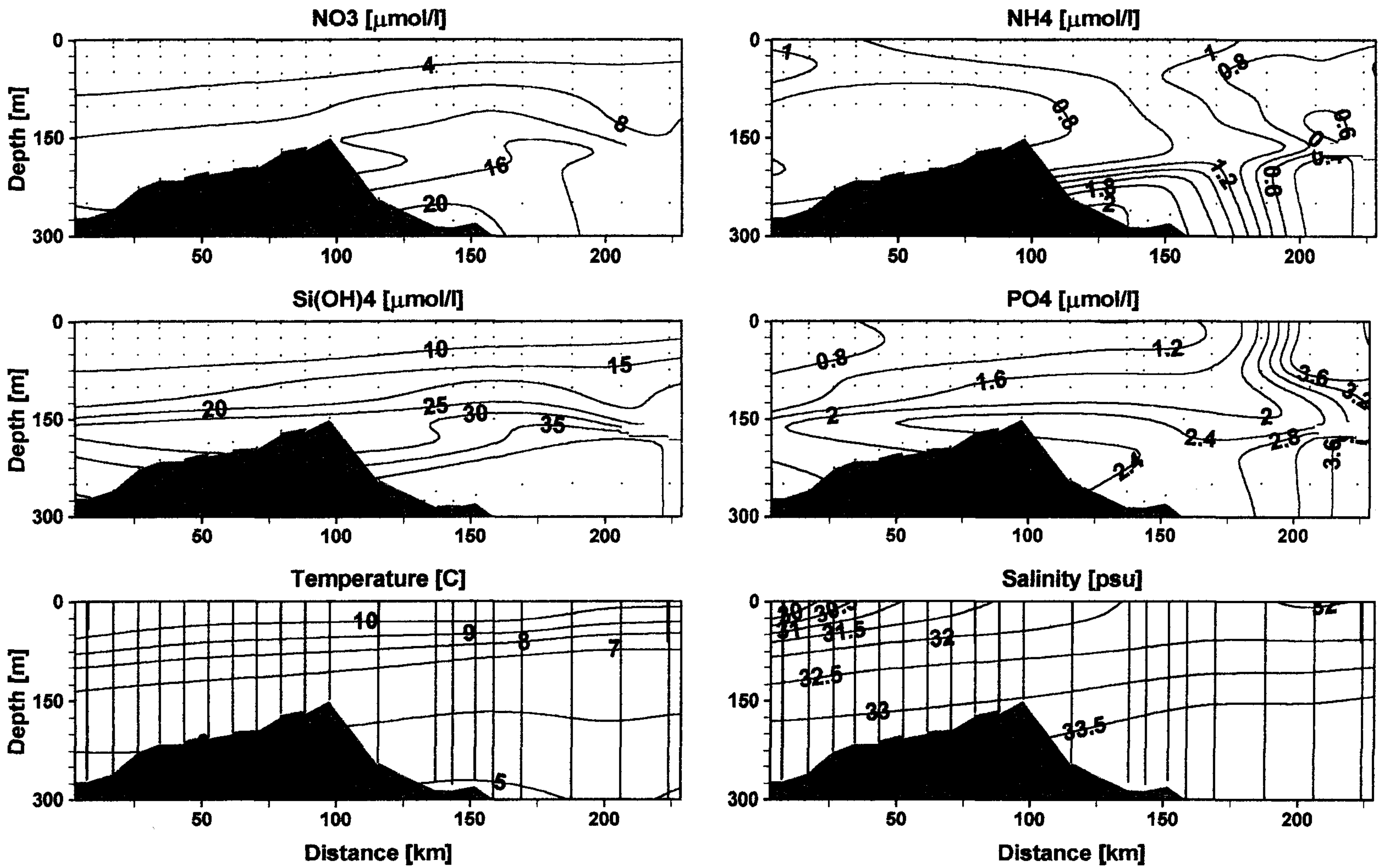
Appendix 1.4 Surface (a) and integrated (surface to 30-50 m) (b) chlorophyll *a* concentrations across the Seward Line March through December 1998. Units are μg chl *a* l^{-1} and mg chl *a* m^{-2}.



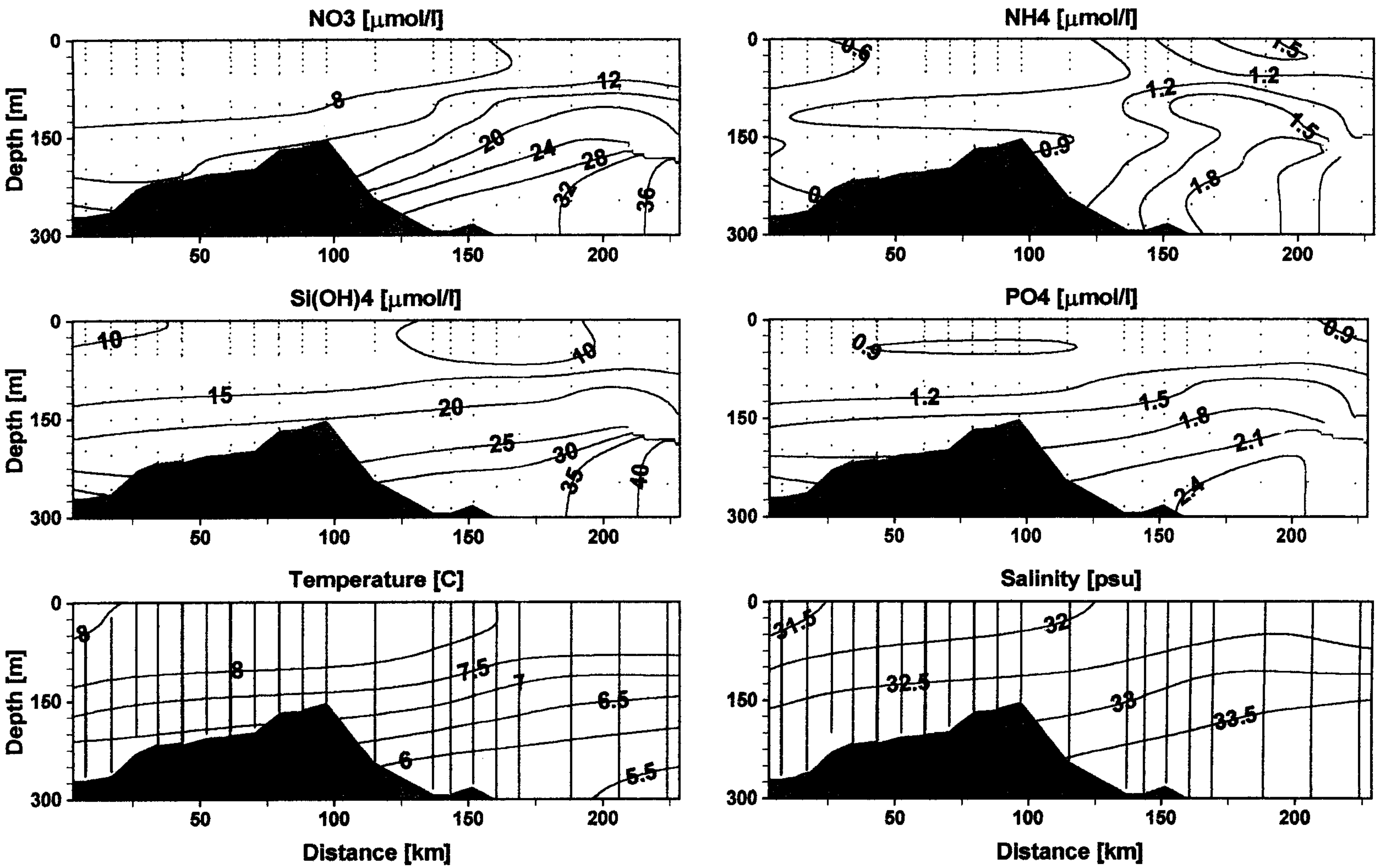
Appendix 1.5 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 7-12 May 1998. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).



Appendix 1.6 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 10-13 July 1998. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).



Appendix 1.7 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 3-8 October 1998. Units are μmole l^{-1} for nutrients, °C, and psu (practical salinity units).



Appendix 1.8 Vertical profiles of a) nitrate, b) ammonium, c) silicate, d) phosphate, e) temperature, and f) salinity across the Seward Line taken 2-4 December 1998. Units are µmole l^{-1} for nutrients, °C, and psu (practical salinity units).