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Deep-Sea Research II 51 (2004) 229–245

DEEP-SEA RESEARCH
PART II

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Satellite-measured seasonal and inter-annual chlorophyll variability in the Northeast Pacific and Coastal Gulf of Alaska[☆]

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Received 23 July 2002; received in revised form 12 May 2003; accepted 12 May 2003

Abstract

Four years (September 1997–August 2001) of SeaWiFS ocean-color satellite data are used to present the first synoptic quantification of chlorophyll variability on seasonal and interannual timescales over the Northeast Pacific and Coastal Gulf of Alaska. Low light levels and/or cloud during November–January prevent examination of winter patterns. The climatological seasonal patterns show shelf-intensified chlorophyll (by a factor of 3 or more) around the entire basin, extending up to 300 m beyond the shelfbreak along the eastern margin and south of Kodiak Island, with peaks in May and again but weaker in August–September. Over the central basin, concentrations are minimum in February ($<0.4 \text{ mg m}^{-3}$), have no spring peak, and increase steadily over the season to a maximum ($\sim 0.7 \text{ mg m}^{-3}$) in September–October. The dominant mode (27% of total variance) of an empirical orthogonal function (EOF) decomposition of the monthly image time series shows interannual variability is strongest during the spring peak around the periphery of the basin with minima in 1998 and 2001. The second and third modes (8% and 7%) capture additional spring interannual variability in patterns strongly related to the shelfbreak west of Kayak Island (144°W) and in more diffuse mesoscale patterns in the eastern GOA. Cross-shelf chlorophyll variability (0–400 km offshore) at three locations contrasts strong seasonality and spring bloom development offshore, over the shelf break, in the northern GOA (off Seward) with weaker seasonality over the shelf off the Queen Charlotte Islands. The shelf between Prince William Sound and Kodiak Island consistently develops a spring along-shelf gradient in chlorophyll, maximum over the western end of the shelf. Comparisons to wind and surface temperature anomalies suggest that interannual differences in the strength of the spring bloom are more strongly related to wind forcing the previous winter than temperature anomalies associated with the 1997/98 El Niño.

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1. Introduction

Superimposed on the basin-scale circulation features of the Northeast Pacific (NEP) and Coastal Gulf of Alaska (CGOA) (Fig. 1) are strong baroclinic forcing and mesoscale physical

[☆] Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.dsr2.2003.06.003

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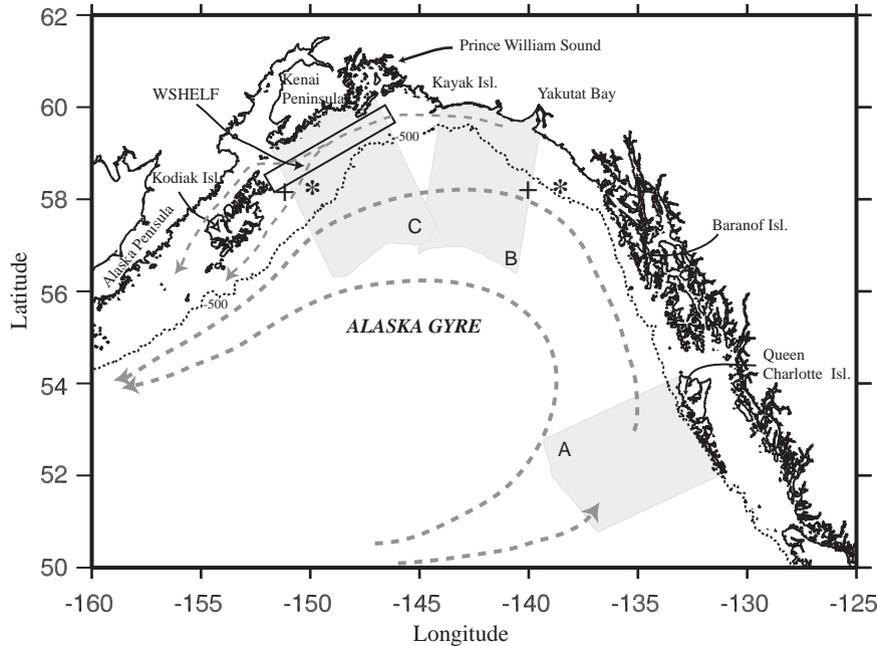


Fig. 1. The NEP and CGOA study region showing the shelfbreak as the 500 m bathymetric contour and major geographic locations. Dashed lines show major current systems. Shaded regions (A–C) show locations sampled to produce time series of cross-shelf chlorophyll profiles. Each region was averaged in the along-shelf direction across the width of the box. Also shown is the location of a 300 km shelf region (WSHELF) extending from Kodiak Island to Prince William Sound, south of the Kenai Peninsula, sampled to produce a time series of along-shelf profiles. Asterisks and plus signs indicate sample locations for SST and wind speed (*) and wind-stress curl (+).

variability (Royer, 1998). This region is a highly commercially productive ecosystem, yet the link between physical processes and phytoplankton variability remains poorly quantified. Phytoplankton biomass cycles are described as non-seasonal over the entire deep-ocean NEP (40–60°N) (Evans and Parslow, 1985). In general, the NEP has low chlorophyll ($<0.5 \text{ mg m}^{-3}$) dominated by small cells ($<5 \mu\text{m}$) and relatively high nutrient levels for much of the year. The high nutrient low chlorophyll condition (HNLC) extends throughout much of the Subarctic Pacific. Spring and summer chlorophyll blooms are distinctly absent, although this general state may be interrupted by anomalous and short-lived phytoplankton blooms (Evans and Parslow, 1985; Frost, 1991; Harrison et al., 1999; Banse and English, 1999). In contrast, the coastal peripheries of the NEP as far north as 55°N show strong seasonality in phytoplankton concentrations including differing phytoplankton and zooplankton community structure and dy-

namics (Boyd and Harrison, 1999; Strom et al., 2001).

Multi-year variations in upper ocean water properties and primary production are reported at Ocean Station Papa (OSP, 50°N, 145°W) in the NEP (Whitney and Freeland, 1999). Strong seasonal variability in primary production, cell-division rates, sedimentation rates, and mesozooplankton biomass and microzooplankton grazing rates are evident over much of the NEP with a winter minimum (Mackas and Tsuda, 1999; Wong et al., 1999; Harrison et al., 1999; Frost, 1993), but phytoplankton standing stocks remain stable year-round (Boyd et al., 1995a, b). There is general agreement that chronic micro-nutrient limitation of large cells, low light availability in winter, a shallow winter mixed layer, and temperature inhibition of micro and mesozooplankton, combined with low over-wintering stocks of mesozooplankton result in near-constant phytoplankton biomass throughout the year

and the absence of spring blooms (Evans and Parslow, 1985; Frost, 1991; Boyd et al., 1995a, b; Boyd and Harrison, 1999; Harrison et al., 1999; Wong et al., 1999). Several of these studies note that temporal variability at OSP and the surrounding HNLC regions in the NEP may misrepresent variability in productive coastal regions north of 50°N.

Major circulation features in the NEP include the Alaskan Gyre, a wind and buoyancy forced cyclonic circulation bounded by the eastward-flowing North Pacific Current along the southern boundary of the study area, the Alaska Current to the east, and the Alaskan Stream to the north and west (Royer, 1998). The Alaskan Stream emerges from convergence of the northward flowing Alaska Current near Kodiak Island and extends as a narrow jet the length of the Aleutian Islands over the continental slope (Chelton and Davis, 1982; Bograd et al., 1999). The Alaskan Coastal Current, on the shelf shoreward of the Alaskan Stream is typically within a few 10s of kilometers of the shore, forced by freshwater input and winds (Johnson et al., 1988; Schumacher and Reed, 1980). Seasonal and interannual variability of surface circulation, sea-surface heights (SSH), and sea-surface temperature (SST) fields has been attributed mainly to freshwater and wind forcing and, to a lesser degree, to remote forcing by waves of tropical origin (Bograd et al., 1999; Matthews et al., 1992; Heim et al., 1992; Royer, 1989; Bhaskaran et al., 1993). The wind field, dominated by the strong Aleutian Low pressure system in winter and the North Pacific High in summer, is primarily downwelling favorable throughout the year along most of the CGOA. Buoyancy forcing by freshwater discharge occurs nearly 5 months out of phase with wind-stress forcing each year (Royer, 1998). Chelton and Davis (1982) proposed that oceanic transport in the Alaska and California Currents varied out of phase over El Niño/Southern Oscillation (ENSO) cycles with enhanced Alaska Current transport during positive ENSO periods. An associated shift in atmospheric circulation is characterized by more intense winter Aleutian lows, warmer than average coastal SSTs, and enhanced southwesterly winter winds in the NEP.

Mesoscale oceanographic features in the NEP and CGOA contribute strong variance to hydrography, SST, and SSH fields, particularly along the shelf/slope boundary (Tabata, 1982; Meyers and Basu, 1999; Bograd et al., 1994; Thomson and Gower, 1998; Okkonen et al., 2001; Crawford et al., 2000). The broad extent of the mesoscale eddy field on the CGOA shelf constitutes a major disruption to alongshore transport of water and results in cross-shelf fluxes of nutrient-rich shelf waters and elevated chlorophyll concentrations to the open ocean (e.g., Okkonen et al., 2003).

Previous satellite-based synoptic views of large-scale chlorophyll variability in the NEP and CGOA using Coastal Zone Color Scanner (CZCS) data were limited by missing data resulting from mission constraints (McClain, 1993; Banse and English, 1994) and inadequate high-latitude atmospheric correction (Strub et al., 1990). Vinogradov et al. (1997) evaluated CZCS-derived winter and summer surface chlorophyll standing stocks over the entire Pacific Ocean but observed no interannual variation. Banse and English (1994) showed that the CZCS-derived mean annual pigment cycle in the Subarctic Pacific (40–60°N) has little seasonality. NEP concentrations rise slowly by a factor of ~ 2 through the year toward a maximum in October/November. This non-seasonality in both chlorophyll biomass observed in the NEP and the eastern Subarctic Pacific arises from a number of factors (e.g., Banse and English, 1999), including chronically low micronutrients, continuous grazing by a permanent standing stock of microzooplankton, and absence of deep winter mixing. In contrast, chlorophyll concentrations $> 1\text{--}3\text{ mg m}^{-3}$ observed north of 55°N were attributed to entrainment of productive shelf waters south into the study area, but neither seasonality nor differences between years could be quantified (Banse and English, 1999). Recently, Gregg (2002) used Sea-viewing Wide-Field-of-View Sensor (SeaWiFS) data to compare seasonal and interannual chlorophyll variability of the North Pacific from 1997 to 2000 to a global coupled physical/biological model, suggesting that significant spring blooms in May of 1999 and 2000 resulted from mixed-layer variability imparting a strong imbalance to auto and heterotrophic

populations. Much of the climatological spring mean chlorophyll values appear around the rim of the N. Pacific and CGOA, although the global model does not resolve shallow (<200 m) coastal areas.

Here, the first four years (September 1997–August 2001) of SeaWiFS data are used to provide a preliminary characterization of seasonal and interannual chlorophyll variability over the NEP and CGOA. The study period includes the 1997/1998 ENSO (Strub and James, 2002). Our goals are to: (1) provide a first synoptic quantification of the spatial pattern, timing and relative magnitude of the large-scale seasonal chlorophyll cycle, (2) quantify the interannual variability in the basin-scale chlorophyll fields over the four available years, and (3) characterize time/space chlorophyll variability on different parts of the highly productive CGOA shelf. We then provide a brief discussion of major chlorophyll features in relation to hydrographic variability documented in the literature and coincident wind forcing and SST anomalies.

2. Data and methods

Daily level-2 global area coverage SeaWiFS chlorophyll data produced with standard NASA algorithms (OC4, O'Reilly et al. 2000) and coefficients (reprocessing 3) were retrieved from the Distributed Active Archive Center (DAAC) at Goddard Space Flight Center. These data were sub-sampled over the study area (50–60°N and 125–160°W) and re-gridded to a cylindrical equidistant projection at 4 km resolution. Multiple orbits from the same day were composited into a single image to produce a time series of daily scenes. Variability is examined by forming 8-day and monthly composites from the daily images, resulting in 45 and 12 scenes per year, respectively. Persistent clouds and seasonally diminished light levels prevent examination of winter months (November–January) and these data are excluded from the analyses. Further averaging by calendar month over the 4 years produced a “climatological” monthly seasonal cycle.

The number of cloud-free images contributing to each monthly composite is weather dependent, spatially and temporally variable and an obvious limitation to the interpretation of the data in this study area. Fig. 2 presents the mean and maximum number of valid retrievals at individual ocean pixels within four quadrants of the study area as a function of month over the study period. The data show strong seasonal dependence as well as regional variability with marginally better coverage over the northwest quadrant. Lack of data in winter months is readily apparent.

Interannual variability is examined using an empirical orthogonal function (EOF) decomposition of the 4-year monthly time series, excluding winter months. The actual months are included online Supplementary material. Pretreatment removed the temporal mean from each pixel and masking excluded the Bering Sea, major glacial bays, fjords, and river outlets from the analysis.

Wind data are monthly averages of the Fleet Numeric Meteorology and Oceanography Center (FNMOC) 10 m equivalent wind speed at 1° spatial resolution and wind-stress curl at $3 \times 1^\circ$ spatial resolution over the NEP. SST anomalies were acquired from climatologies (Reynolds and Smith, 1994) located at the International Research Institute/Lamont-Doherty Earth Observatory Climate Data Library.

3. Results

3.1. Seasonal cycles

Climatological monthly composites computed from 4 years of SeaWiFS observations (Fig. 3A and B) provide the most comprehensive synoptic views of seasonal chlorophyll variability over the entire NEP to date. The dominant spatial pattern (Fig. 3A) is elevated chlorophyll concentrations distributed peripherally, shelf-intensified throughout the year by factor of 3 or more relative to offshore regions (Fig. 3B). Highest concentrations ($> 3 \text{ mg m}^{-3}$) are observed on the wide shelf west of the Prince William Sound region ($\sim 145^\circ\text{W}$), extending seaward of the shelfbreak near Kodiak Island (152°W) and southwest along the Alaska

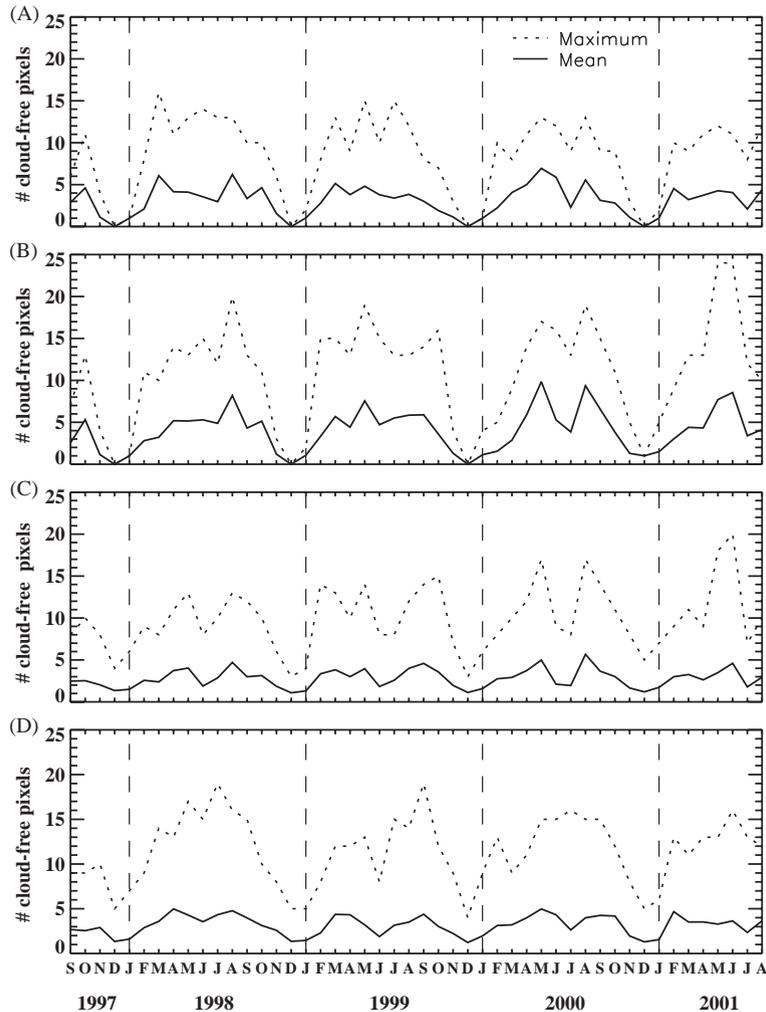


Fig. 2. The amount of cloud-free data contributing to each monthly composite is summarized. The mean and maximum number of valid chlorophyll retrievals at individual pixel locations in each month within each of 4 equal area quadrants of the study area is shown for the study period. Quadrant boundaries are (A) northeast, 142.5–125°W, 56–62°N, (B) northwest, 160–142.5°W, 56–62°N, (C) southwest, 160–142.5°W, 50–56°N, and (D) southeast, 142.5–125°W, 50–56°N.

Peninsula beginning in April. In the eastern GOA, high chlorophyll concentrations ($> 2 \text{ mg m}^{-3}$) are present over the narrower shelf south of 58°N and extend seaward of the shelfbreak. Patches of high chlorophyll concentration also are observed in all months over shallow bathymetry ($< 100 \text{ m}$) on the eastern shelf region near the Queen Charlotte Islands, Vancouver Island, and Kodiak Island. The patch of elevated chlorophyll ($> 1 \text{ mg m}^{-3}$) centered at 52°N, 145°W in June results from an

extensive offshore bloom during the first half of June 2000 (Supplementary material).

The climatological seasonal cycle shows chlorophyll concentrations in February are $< 0.5 \text{ mg m}^{-3}$ over deep waters and $< 1.0 \text{ mg m}^{-3}$ over the shelf (Fig. 3B). In March, the $> 1.0 \text{ mg m}^{-3}$ chlorophyll region covers the entire shelf region and extends beyond the 500 m isobath. By April, concentrations are visibly enhanced over the shallow ($< 100 \text{ m}$) regions, embayments, and in

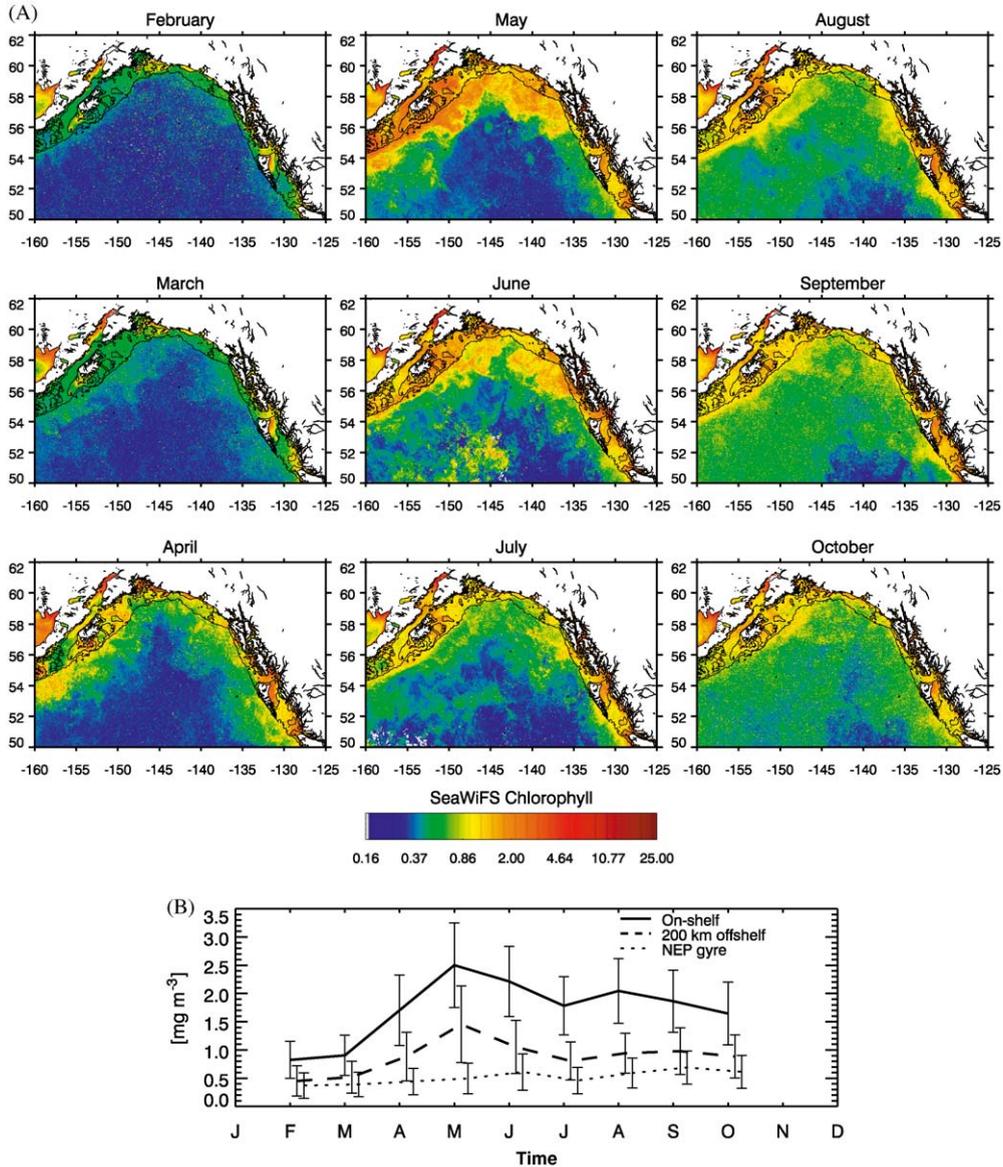


Fig. 3. (A) Climatological (1997–2001) monthly SeaWiFS chlorophyll (mg m^{-3}) for showing the annual cycle over the period (February–October) with maximum data coverage (Fig. 2). (B) The annual cycles of mean chlorophyll concentration over the main CGOA shelf (<500 m, solid line) (excluding smaller embayments and fjords), a 200 km wide band immediately seaward of the shelfbreak (dashed line), and offshore of this over the central NEP gyre (dotted line). Error bars represent one-half the SeaWiFS chlorophyll standard deviation.

a patchy field spanning the shelfbreak along the Alaska Peninsula from 144°W to 160°W . Maximum chlorophyll concentrations occur in May, with mesoscale patterns of high pigment

(> 1.0 mg m^{-3}) extending up to 300 km beyond the shelfbreak from 135°W to 150°W . The presence of strong mesoscale patterns in the 4-year climatology suggests that features appear

each spring (April–June) at similar locations and times or that missing data biases images. Examination of individual months confirms the recurrence of these features in multiple years although both missing data and only 4 years of data availability undoubtedly contribute to the patterns. In June, peripheral concentrations decrease and the cross-shelf spatial extent of elevated chlorophyll values is reduced. By July, concentrations $> 2.0 \text{ mg m}^{-3}$ are closely constrained to the narrow shelf. A weaker seasonal maximum occurs in August/September as a moderate increase in concentrations on the shelf ($< 500 \text{ m}$) and a broad increase across the entire basin. Concentrations then decrease across the entire study region in October. In offshore regions, seasonality is minimal but chlorophyll increases steadily from a low of 0.35 mg m^{-3} in February to a relative maximum of 0.7 mg m^{-3} in September (Fig. 3B).

3.2. Inter-annual variability

The first three modes of the EOF analysis explain 42.5% of the total chlorophyll variance and isolate dominant space/time features of the seasonal and interannual variability. The spatial pattern of the first mode (Fig. 4A, 27.4% of the variance) reveals the peripherally intensified chlorophyll evident in the climatological seasonal cycle (Fig. 3B) with mesoscale patterns extending seaward of the 500 m isobath north of $\sim 55^\circ\text{N}$ and weak values over the central NEP. The amplitude time series (Fig. 4A) show this pattern is modulated by the general seasonal cycle and quantifies interannual variability. Chlorophyll concentrations are minimum in winter (February, March), peak in spring (May/June) and again in early fall (August/September). An overall increase in concentration from February through October

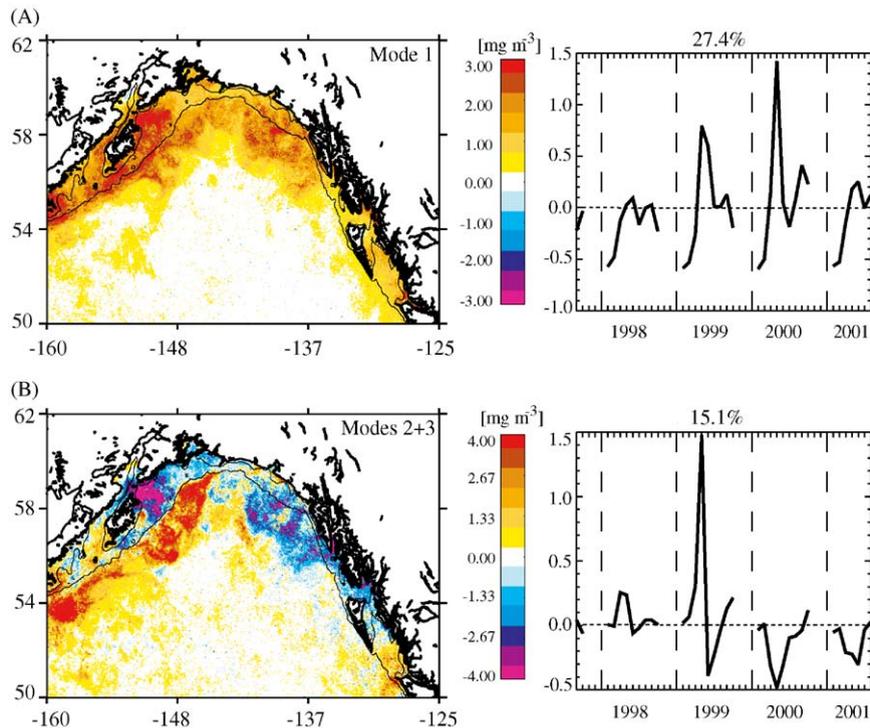


Fig. 4. EOF decomposition of the monthly image time series (excluding winter, November–January) showing (A) the dominant mode (27.4% of the variance) and its associated time series, and (B) the summed second and third most dominant modes (15.1% of the total variance) and their associated time series. The temporal mean is removed from each pixel and masking is applied to exclude pixels from the heads of major bays, fjords and river outlets (white regions inshore of the shelfbreak in mode 1).

is superimposed on this cycle in each complete year sampled. Both late winter (February–March) and mid-summer (July) amplitudes are relatively constant over the 4 years. The strongest interannual variability is evident as differences in both amplitude and timing of the spring peaks (Fig. 4A). The annual cycle and especially the spring peak are weakest in 1998. The spring maximum is strongest in 1999 and 2000 and relatively weak again in 2001. These patterns are evident but difficult to quantify in the actual scenes (Supplementary material). The duration of the spring maximum extends through both May and June in 1998, 1999 and 2001, but is clearly limited to May in 2000. The fall peak occurs consistently in September, strongest in 2000 and weakest in 1997 and 1998. Low offshore values in the spatial pattern imply weak seasonality and associated interannual variability over the main NEP basin.

Both the second and third mode (8.5% and 6.6% of the variance, respectively) capture additional (by definition, uncorrelated) variability associated with the spring period in mesoscale patterns on the shelf and within ~ 300 km of the shelfbreak. As in the first mode, their spatial patterns are weak over the open basin. These modes are presented as a sum (mode 2+3, Fig. 4B), contributing 15% of the total chlorophyll variability. West (downstream) of Kayak Island (144°W), the spatial pattern shows a strong relationship to bathymetry with high positive values immediately seaward of the shelfbreak and negative values on the shelf. In the eastern GOA (east of $\sim 144^\circ\text{W}$), more diffuse mesoscale features straddle the shelfbreak as high negative values in the spatial pattern. Positive peaks in the associated time series indicate enhancement of spring (April–May) chlorophyll within the patterns seaward of the shelfbreak in western GOA and along the Alaska Peninsula, maximum in 1999, present in 1998 but weak in 2000 and 2001. This is followed (May–June) by amplification of spring/summer concentrations (negative peaks in the time series) on the shelf east of Kodiak Island together with enhancement of the more diffuse of mesoscale features in the eastern GOA. This (negative) pattern is weak (or absent) in 1998

and maximum in June of 1999 and 2001 and May of 2000.

3.3. Cross-shelf and along-shelf variability

Details of cross-shelf chlorophyll variability in three locations (see Fig. 1) are examined as a function of time using the increased temporal resolution afforded by 8-day composite images (Figs. 5–7). Pattern visualization is assisted by applying a 3-point linear smoothing operator in time and space (cross-shelf contours) and by further filling of small gaps due to clouds along the spatial dimension within each time step (along-shelf contours). Filling across temporal gaps was not attempted and gaps greater than the filter extent and winter periods were not filled. Region A is located in the southeast portion of the study area over the narrow shelf off the Queen Charlotte Islands, immediately north of the North Pacific Current bifurcation. Region B extends over the wider shelf north of this between Yakutat Bay and Kayak Island, extending across the Alaska Current. Region C samples across the broad shelf off the Kenai Peninsula, sampling across the strong variability in the Alaskan Stream observed in Fig. 3.

Cross-shelf chlorophyll profiles in each region from 1997 to 2001 shows the expected pattern of shelf-intensification. The general seasonal pattern shows chlorophyll concentrations increasing on the inner shelf in March/April followed by rapidly increasing concentrations in April/May that occur over the shelf and well beyond the shelfbreak. The collapse of the spring chlorophyll peak begins offshore, proceeding onto the shelf by June. Low chlorophyll values ($<0.75 \text{ mg m}^{-3}$) are present off the shelf in all regions in summer. In August/September chlorophyll concentrations increase again, but with less cross-shelf extension than that of spring. Weakening and collapse of the fall maxima occurs by October/November in all regions. Variability on this general pattern is apparent. The relatively narrow shelf of Region A has the weakest seasonality, the lowest overall concentrations and the smallest offshore extension of elevated spring/fall concentrations (Fig. 5A and B). In contrast to the other regions, the spring

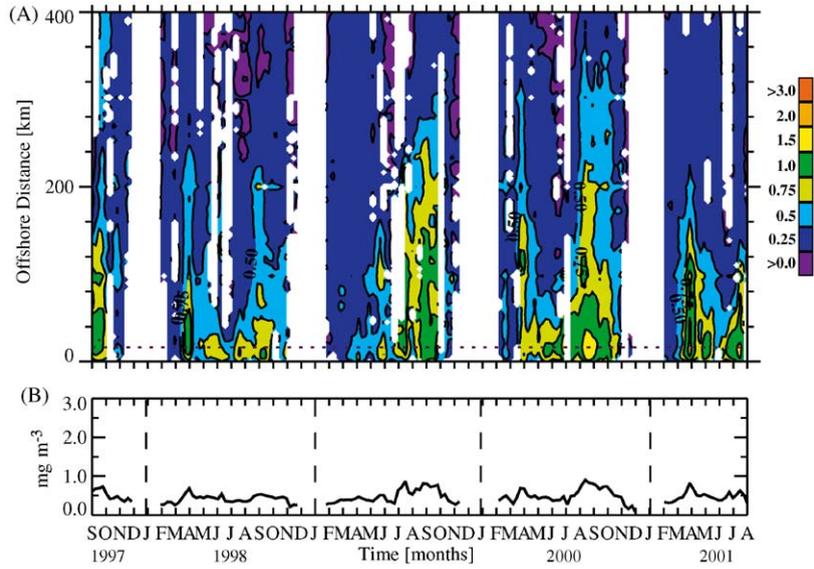


Fig. 5. (A) Cross-shelf profiles of chlorophyll concentration (mg m^{-3}) from region A (see Fig. 1) sampled from 8-day composite images, contoured as a function of time and distance offshore (0–400 km). Each cross-shelf value represents a spatial average of chlorophyll equidistant from the coast over approximately 220 km of coastline. The dash line is the mean position of the 500 m isobath. (B) Chlorophyll concentration averaged over the entire cross-shelf profile as a function of time.

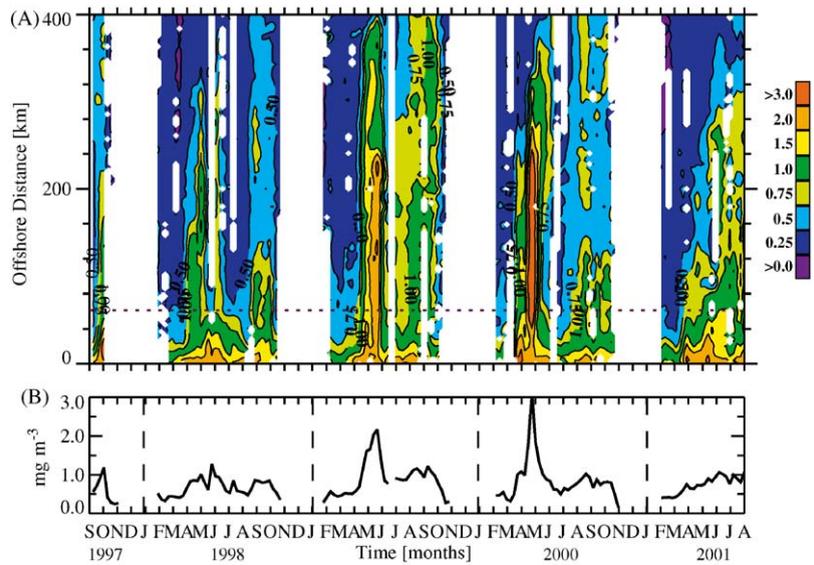


Fig. 6. Same as Fig. 5 but for region B (see Fig. 1).

peak at Region A is relatively weak compared to the increase and cross-shelf extension of elevated chlorophyll in August/September. Region

B (Fig. 6A and B) has higher overall concentrations and stronger seasonality with maximum concentrations adjacent to the coast in each year

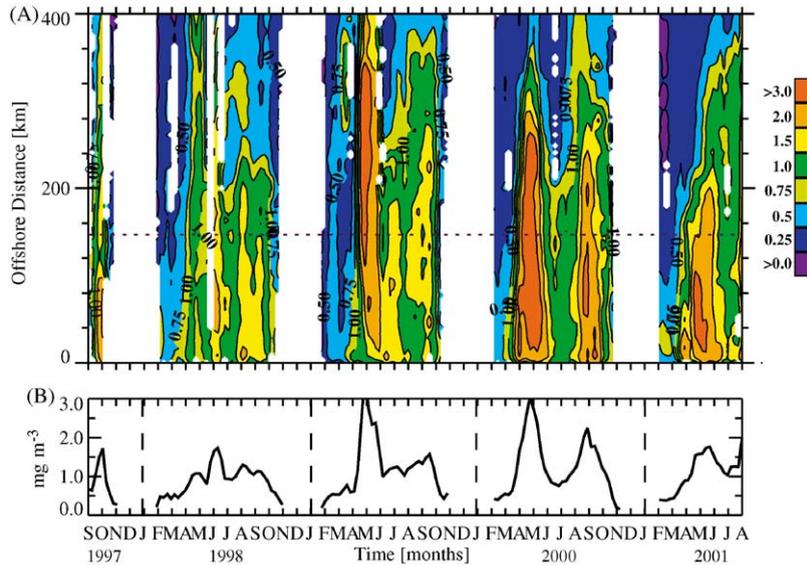


Fig. 7. Same as Fig. 5 but for region C (see Fig. 1).

except 2000. Region C has the highest spring chlorophyll concentrations, greatest offshore extent (>400 km) of spring/fall elevated concentrations with seasonal maxima that clearly develop offshore, dissociated from the coast in each year (Fig. 7). Interannual variability in regions B and C shows mean spring chlorophyll concentrations are 2–3 times higher in 1999 and 2000 than 1998 or 2001 (Fig. 6B and 7B). In region C, the offshore extent of the 1.5 mg m⁻³ contour exceeds 400 km in May 1999, with a 200 km wide region of high chlorophyll (>3.0 mg m⁻³) located almost entirely seaward of the shelfbreak. Maximum fall concentrations are again centered over the shelfbreak rather than adjacent to the coast. In both 2000 and 2001, elevated spring and late summer/early fall chlorophyll concentrations (>3.0 mg m⁻³) are centered over the shelf. Visual inspection of 8-day images shows that a portion of this variability in the cross-shelf position of high chlorophyll is associated with the position of the Alaskan Stream and mesoscale features immediately seaward of the 500 m isobath in 1999, consistent with the strength of positive patterns in EOF Modes 2 + 3 in 1999 (Fig. 4).

The wide shelf region between Kodiak Island and Prince William Sound is among the

most biologically productive in the NEP. Along-shelf chlorophyll variability, sub-sampled from the time series of 8-day composites, over a 300 km segment of this shelf (see Fig. 1) is shown as a function of time (Fig. 8A). Early in the season (February–March), concentrations are higher (>0.75 mg m⁻³) at the northeastern end of the shelf. In spring (April–May), concentrations increase rapidly across the entire shelf reaching a maximum in May. This increase is strongest and earliest on the southwestern portion of the shelf creating an along-shelf gradient, maximum between ~140 and 190 km in spring (Fig. 8A and B). A multi-year average of the April–May along-shelf profiles shows a ~2-fold difference in mean chlorophyll concentration between the southwestern and northeastern portions of this shelf (Fig. 8B). This along-shelf gradient is readily apparent in the spatial patterns of both EOF modes (Fig. 4). By June–July, both actual concentrations and the along-shelf gradient diminish over the entire region (Fig. 8A and B). Elevated chlorophyll concentrations reform in the fall (August–September), more strongly on the southwestern end. Examination of interannual variability shows 1998 spring and fall chlorophyll concentrations are

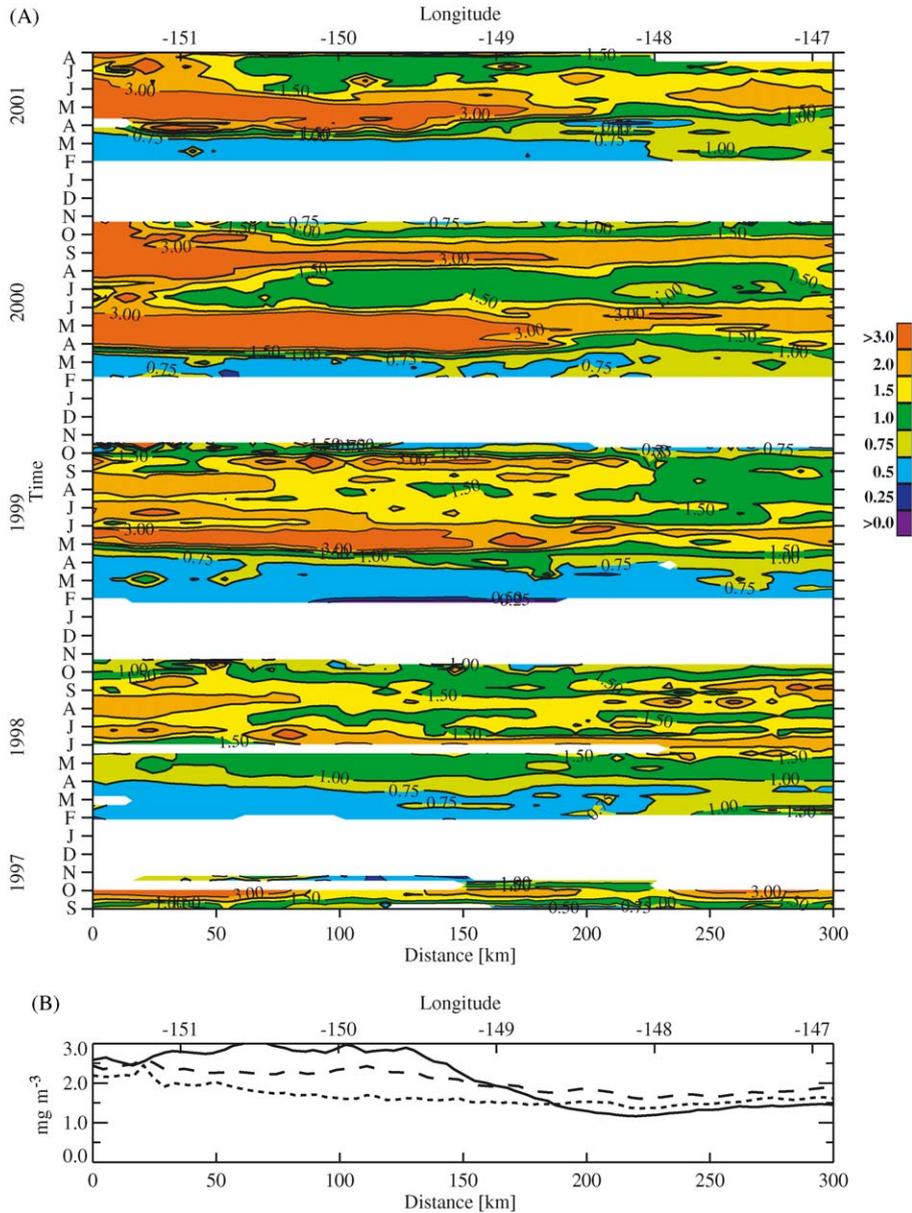


Fig. 8. (A) Profiles of along-shelf chlorophyll concentration (mg m^{-3}) sampled from 8-day composite images, contoured as a function of time and distance along a 300 km shelf segment shelf between Kodiak Island and Prince William Sound (see Fig. 1). Concentrations at each location are a spatial mean across a 40 km wide swath. (B) Four-year average profiles from April–May (solid line), June–July (dash-dot line) and August–September (dashed line) show the overall seasonal pattern of along-shelf chlorophyll distribution and the strong spring along-shelf gradient.

relatively weak (rarely $> 3.0 \text{ mg m}^{-3}$) and elevated values are both spatially and temporally patchy. Both spring and fall blooms are strongest in 2000.

4. Discussion

The SeaWiFS imagery provides spatial context and synoptic quantification of seasonal variability

that is relatively well established at localized sites in the NEP. The overall seasonal increase in chlorophyll concentration from February until October (Figs. 3 and 4) is consistent with previous observations over the Subarctic Pacific (Banse and English, 1994). The fall increase has been described as a response to relaxation of grazing pressure by micro and macro zooplankton (Evans and Parslow, 1985; Frost, 1991; Harrison et al., 1999) and/or the seasonal addition of macronutrients and iron to high nutrient low chlorophyll (HNLC) waters of the NEP by aerial deposition or entrainment of nutrient-rich coastal water into the offshore regions (Banse and English, 1994, 1999; Harrison et al., 1999). Interannual variability in the timing, magnitude, and duration of the basin-wide seasonal cycle (see Figs. 3b and 4a) is dominated by chlorophyll variability on the CGOA shelf. Across this extensive shelf area, the timing and magnitude of the spring and fall blooms on the eastern shelf regions (Fig. 5) can be contrasted with the western shelf (Figs. 7–9). These two shelf regions differ in width, total area, bathymetric complexity, local wind and freshwater forcing, and coastal circulation over the outer shelf and slope (Royer, 1998). On the shelf between Kodiak and Prince William Sound (Fig. 8A), the earlier spring chlorophyll bloom in the west (downstream) implies along-shelf variability in wind, freshwater, and bathymetric forcing that produce concomitant horizontal gradients in the stratification, SSH, and vertical mixing (Royer, 1998; Okkonen et al., 2003; Macklin et al., 1990).

A significant portion of the interannual chlorophyll variance is associated with mesoscale features (80–300 km scales) evident in the imagery along the shelfbreak and extending up to ~300 km beyond. The positions of these features in both the climatological monthly scenes and the EOF modes are consistent with previous work documenting eddy dynamics in the study area revealed in SST imagery (Thomson and Gower, 1998), drifter trajectories (Bograd et al., 1999) and altimeter data (Okkonen, 1992; Meyers and Basu, 1999; Crawford et al., 2000). In the eastern portion of the study area, persistent mesoscale chlorophyll features offshore of Baranoff Island and extending north along the shelfbreak (Figs. 3 and 4) are

located in the region of the anticyclonic Sitka eddy (Tabata, 1982) and eddies that develop within the Alaska Current (Crawford et al., 2000). Southeast of Kodiak Island is a mesoscale feature that appears in May of 1999 and 2000 (but not in 1998) consisting of filaments and fronts extending up to 200 km off the shelf. Daily image sequences (not shown) indicate this probably results from meandering of the Alaskan Stream forming an anticyclonic eddy. Elevated chlorophyll concentrations over the continental slope along the Alaska Peninsula are closely associated with relatively warm water marking the position of the Alaska Stream shown by Thomson and Gower (1998) and eddies/meanders embedded within this flow evident in altimeter data (Crawford et al., 2000; Okkonen et al., 2003). The connections between shelf and offshore mesoscale patterns of elevated chlorophyll in the Alaskan Stream are consistent with previous conclusions (Banse and English, 1999) that elevated chlorophyll concentrations ($> 1\text{--}3 \text{ mg m}^{-3}$) around the periphery of the NEP result from entrainment of productive shelf waters into the Alaskan Gyre.

The 4-year SeaWiFS time series includes the 1997–98 El Niño event. The positive phase of the ENSO cycle is associated with an intensification of Hollowed and Wooster's (1992) type "B" circulation in the NEP and CGOA, characterized by more intense winter Aleutian lows, greater precipitation, warmer coastal SSTs, enhanced southwesterly winter winds, and increased advection into the Alaska Current (Murray et al., 2001; Okkonen et al., 2001). The seasonal intensification of geostrophic transport around the Alaskan Gyre, in phase with the seasonal maximum in wind forcing (November–January) is further amplified during El Niño (Strub and James, 2002). Wind-stress curl is positively correlated with gyre circulation and mesoscale eddy activity (Murray et al., 2001; Okkonen et al., 2001). However, as stronger cyclonic winds over the NEP result in increased downwelling-favorable wind stress over the CGOA, it is not clear that such winds would directly enhance shelf phytoplankton.

Variability of SST and wind forcing over the study period are shown in Fig. 9 for comparison with the associated signal of shelf chlorophyll east

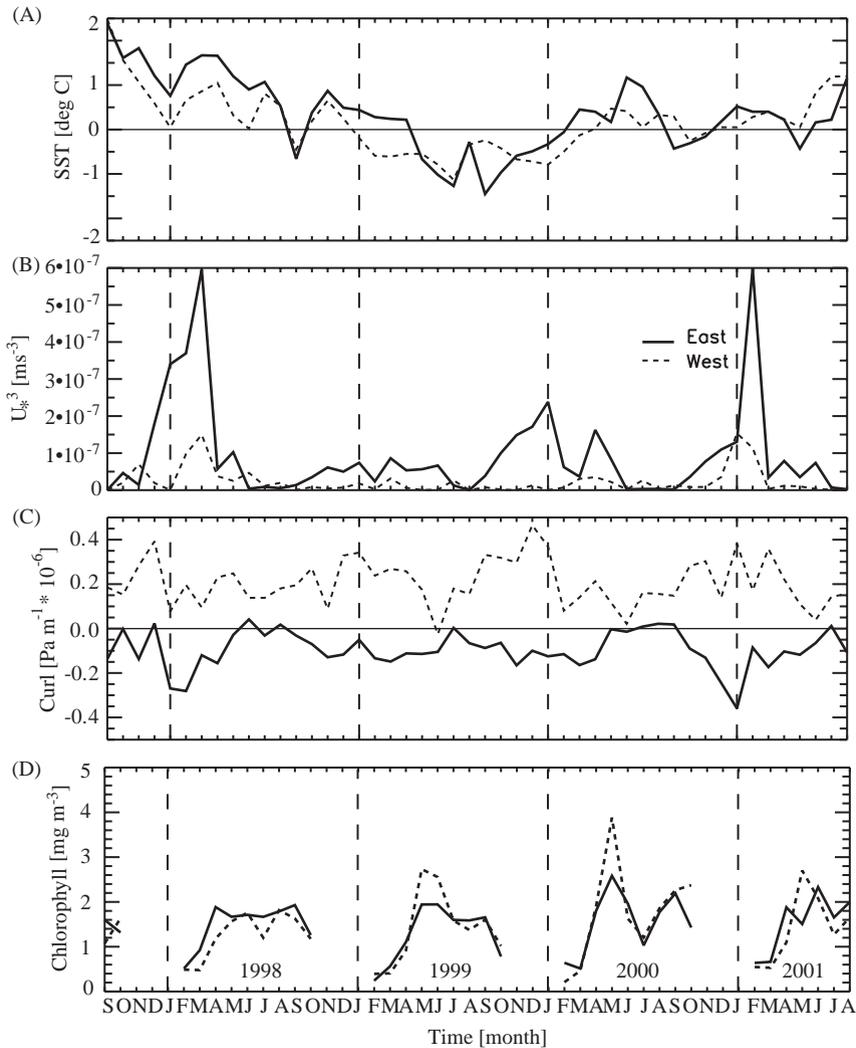


Fig. 9. (A) Monthly mean SST anomalies over the study period from the Reynolds and Smith (1994) climatology from 58°N at 139°W and 150°W (see Fig. 1). (B) Monthly mean wind mixing strength (as u_*^3) from $3^{\circ} \times 3^{\circ}$ boxes centered at the same locations (C) monthly mean wind-stress curl from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) in the western and eastern CGOA and (D) Average shelf chlorophyll (coast to 500 m isobath) east (solid) and west (dash) of Kayak Island. In A–C, the regions are averaged over $3^{\circ} \times 3^{\circ}$ boxes centered at approximately 58°N and 152.5°W and 141.5°W (see Fig. 1).

and west of Kayak Island and the main features of overall interannual variability evident in Fig. 4 (Mode 1, EOF). Monthly SST anomalies (Fig. 9A) contrast sites at similar latitudes in the eastern and western GOA (139°W and 150°W), and are strongly correlated through the time series. Both are strongly positive in late 1997, diminishing but remaining positive through most of 1998, and reach a minimum in 1999, consistent with in-

creased northward transport in the Alaska Current (Strub and James, 2002) during the El Niño period. The magnitude and temporal persistence of positive anomalies are strongest in the east, lasting until April 1999. Beginning in May 1999, SST anomalies at the two locations become more similar.

Monthly values of wind mixing, characterized as u_*^3 , and wind-stress curl (Fig. 9B and C,

respectively) also contrast conditions in the western and eastern GOA over the study period. The strong annual signal in the eastern GOA resulting from the seasonal shift in position of the Aleutian Low is evident but weaker in the western GOA. Seasonal patterns show a strong winter maximum in mixing strength at both locations. In the east, a winter maximum in negative curl is associated with the seasonal strengthening of the Aleutian low. A fall/winter maximum in positive curl occurs at the western site. The clearest interannual signal is of stronger winter wind mixing in both the east and west GOA accompanied by stronger winter negative curl in the east in the winters of both 1997/1998 and 2000/2001. The positive wind-stress curl characteristic of winter over the western GOA is weakest in 1997/1998. These signals are consistent with the “downwelling index” and sea-level height anomalies at Alaska stations shown by [Strub and James \(2002\)](#) for the 1997/98 El Niño period. These authors do not analyze data from the 2000/2001 period.

We can speculate on relationships between the observed anomalous SST, wind mixing and wind-stress curl time series that would be consistent with observed interannual differences in the large-scale surface chlorophyll signals and on differences between those of the eastern and western CGOA. The CGOA is characterized as relatively rich in nutrients but light limited by persistently low water-column stability ([Polovina et al., 1995](#); [Gargett, 1997](#); [Boyd and Harrison, 1999](#)), a condition potentially altered during years of strong freshwater input, warmer SST and/or reduced wind forcing. Stronger wind mixing and increased downwelling in winter and early spring of 1997/1998 and 2000/2001 could inhibit the seasonal development of stratification, resulting in relatively weak and/or delayed spring blooms ([Figs. 4 and 9](#)). On the spatial scales examined here, this wind forcing opposes and might override any stabilization furnished by increased coastal runoff and anomalous SST during the 1997/98 El Niño period. On the other hand, the combination of elevated SST and enhanced “downwelling index” may combine to limit nutrient availability by increasing vertical and horizontal density gradients, damping normal mixing processes over

the entire CGOA shelf and resulting in the irregular and weaker spring bloom observed on both east and west CGOA in 1997/1998. Years of normal SST, weaker winter mixing (1998/1999 and 1999/2000) and/or decreased downwelling (increased upwelling in the west) allow larger spring phytoplankton blooms. An additional factor may be related to phasing of trophic levels. Temporal delays in seasonal primary productivity allow meso/microzooplankton grazing and reproduction to keep pace with phytoplankton biomass, increasing the impact of grazing on chlorophyll standing stocks. [Rand and Hinch \(1998\)](#) note that stronger winter wind stresses leads to elevated zooplankton biomass around the CGOA the following spring, but this does not persist into the summer. El Niño-associated warmer temperatures and/or advection of reduced biomass or even different species assemblages may contribute to reduced chlorophyll in spring of 1998 but do not explain low concentrations in 2001.

5. Summary

The first 4 years of SeaWiFS chlorophyll data provide the most comprehensive view to date of large-scale seasonality and interannual variability in the NEP and CGOA. Lowest chlorophyll concentrations ($<0.7 \text{ mg m}^{-3}$) and minimal seasonality occur in the center of the Alaskan Gyre. Elevated chlorophyll concentrations with strong seasonal cycles and interannual variability are present around the CGOA on the shelf and within $\sim 300 \text{ km}$ of the shelfbreak. In these peripheral waters, minimum concentrations ($<1.0 \text{ mg m}^{-3}$) are in February/March, the spring maximum is in May, summer concentrations decrease and a secondary early fall maximum occurs in August/September. Over the entire region, superimposed on any seasonal signal is an overall increase in chlorophyll over the year of $\sim 2 \times$ between that of February–March and that present in September–October. Clouds and low light prevent measurements in winter.

Spatial patterns evident in the imagery suggest that elevated chlorophyll concentrations along the shelfbreak and immediately seaward of this are

associated with mesoscale eddies, consistent with previously published work documenting the position and dynamics of both cyclonic and anti-cyclonic eddies in the Alaska Current and the Alaskan Stream. It is evident that eddies have the potential to control a significant proportion of the spatial pattern and temporal variability of phytoplankton biomass in peripheral regions of the NEP. Details of relationships between eddies and mesoscale chlorophyll features and the role of eddies in controlling phytoplankton variability are beyond the scope of this work but approachable with the ocean color and altimeter satellite data now available.

The strongest features of interannual variability are evident in spring (April–May) concentrations on the shelf and extending offshore over the first ~300 km seaward of the shelfbreak. Weak spring chlorophyll concentrations in 1998 are coincident with positive SST anomalies and follow relatively strong winter wind mixing and negative wind-stress curl, potentially associated with the 1997/98 El Niño. Strong spring blooms in 1999 and 2000 follow relatively weak winter wind mixing and reduced negative wind-stress curl. The weak spring bloom in 2001 is not clearly associated with any strong SST anomalies but does follow strong winter wind mixing and downwelling favorable conditions. These data are consistent with previously published work suggesting that NEP/CGOA phytoplankton are primarily light limited. The similar relationship between spring chlorophyll concentrations and winter wind forcing in 1998 and 2001 suggest that these patterns are strongly influenced by wind forcing in addition to biological or hydrographic anomalies resulting from the El Niño conditions present in 1997/98.

Persistent clouds and low sun angles will always present a challenge to analysis of ocean color data for this region. Continuing systematic collection of ocean-color satellite data from both SeaWiFS and other missions will improve the quantification of both the climatological annual patterns and the time/space patterns of interannual variability shown as preliminary findings here. The extent to which these first 4 years of coverage are representative of longer-term variability is unknown. The data do encompass the end of the strongest El

Niño on record but are insufficient to address variability associated with the decadal-scale regime shift suspected to have occurred in 1998/99 (Mantua and Hare, 2002).

Acknowledgements

We thank P.T. Strub and W. Crawford for helpful discussions, the NASA Goddard SeaWiFS team for their efforts in managing SeaWiFS and FNMOC and LDEO for making the wind and SST data sets, respectively, available. This work was funded by NSF Grants OCE-9711919 and 0000899 (part of the US GLOBEC Program) and NASA Grants NAG5-6558 and 6604 (ACT). Contribution no. 384 from the US GLOBEC program.

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