Summer phytoplankton production and transport along the shelf break in the Bering Sea

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Abstract—A general model is presented for the production and fate of phytoplankton during summer in two regions over the continental shelf of the Bering Sea. We propose that both regions of productivity are supported by nutrients transported into the area with the Bering Slope Current and that the fate of the phytodetritus produced is significantly affected by advection. We hypothesize that one system of primary productivity is initiated at the Bering Sea shelf-break front and continues into the northern Bering Sea as part of the modified Bering Shelf water mass. Phytodetritus produced in this system is transported north through Anadyr and Shpanberg Straits and we estimate that in 1987 it supplied 26% of the daily carbon demand of the benthos in the Chirikov Basin. The second region of primary productivity is located in the northern Bering Sea. Nutrients from the Anadyr Current, the northern branch of the bifurcated Bering Slope Current, support a highly productive phytoplankton bloom throughout the summer. Phytodetritus produced in this surface bloom is probably advected into the southern Chukchi Sea and deposited in the sediments.

INTRODUCTION

Our understanding of the magnitude, location and fate of primary production in the vicinity of the Bering Sea continental shelf is increasing rapidly. Results from recent studies in the region suggest that processes contributing to annual production on the shelf include: production due to epontic ice algae (McRoy and Goering, 1974); spring ice-edge blooms (Niebauer and Alexander, 1985), which follow the receding ice edge from deep water onto the shelf; spring blooms over the shelf, which are maintained into the summer by occasional wind mixing events (Sambrotto et al., 1986); spring blooms at the shelf-break front (Iverson et al., 1979a); and summer production on the northeastern shelf (Springer, 1988).

The northern Bering and southern Chukchi Seas have been the subject of extensive oceanographic surveys since 1985 as part of the Inner Shelf Transfer and Recycling (ISHTAR) program. The program was designed to assess the fate of the dissolved and particulate phases of carbon, nitrogen, phosphorus and silicon in the northern Bering and southern Chukchi Seas (Walsh et al., 1989). A primary motivation for this effort

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was the desire to understand the processes sustaining the rich ecosystem known to exist in this subpolar region. Field studies conducted over the past few decades have resulted in a nearly comprehensive understanding of the regional physical oceanography (Coachman et al., 1975). A survey of primary productivity in the area (Sambrotto et al., 1984) provided an initial estimate of the potential magnitude of primary productivity but an incomplete explanation for the processes controlling it.

Early in the ISHTAR program, regions exhibiting major phytoplankton blooms were mapped, and rates of primary production quantified, in the northern Bering and southern Chukchi Seas (Springer, 1988). These highly productive areas were assumed to be the major sources of organic carbon and nitrogen necessary to support the rich higher-trophic populations known to thrive in the Chirikov Basin, of the northern Bering Sea, and in the southern Chukchi Sea (Grebmeier, 1987; Springer, 1988). However, the accepted paradigm for the production and fate of organic matter did not, in our view, completely survive close scrutiny. For instance, a spatial discrepancy existed between the location of the major bloom in the northern Bering Sea (Springer, 1988) and the location of maximum benthic biomass in the same region (Grebmeier et al., 1988). The highest concentrations of benthic biomass were located 20–30 km to the east of the major phytoplankton bloom. It did not appear physically possible, in this strong northerly advective system, to deposit organic carbon and nitrogen such a distance to the east of the bloom. It was clear that we had not fully elucidated the sources and fate of particulate organic nitrogen and carbon over the northern Bering Sea shelf.

Earlier studies of the southeastern Bering Sea shelf (PROBES) resulted in models of the general circulation (Coachman, 1986) and primary productivity patterns (Sambrotto et al., 1986) upstream of the ISHTAR study area. Iversen et al. (1979b) noted that a spring chlorophyll maximum found over the shelf-break front in the southeastern Bering Sea persisted for about 1 month, slowly sinking at a rate of about 1 m d⁻¹. We propose that this shelf-break system of productivity continues along the front to the northwest toward Cape Navarin, and with the Bering Slope Current, extends across the Gulf of Anadyr and through Anadyr and Shpanberg Straits. This production and transport process is analogous to a continuous culture system where, as the plants are transported and grazed, a ready supply of nutrients maintain the phytoplankton at high levels. Malone et al. (1983) described a similar production and transport process at the shelf break of the New York Bight. They found that development of stratification in nutrient-rich offshore water between storm events results in high growth rates and biomass near the surface on the shelf side of the shelf-break front. During the summer, and as we propose to be the case at the Bering Sea shelf break, plant growth occurred at the pycnocline. Unlike the Bering Sea, however, where transport is from the shelf-break front to the inner shelf, up to 35% of annual production over the continental shelf of the New York Bight is exported from shelf to slope water.

A second important region of summer production is associated with the western boundary current (the northern extension of the Bering Slope Current known as the Anadyr Current) south of Bering Strait. Nutrients from the Anadyr Current support intense surface production following passage through Anadyr Strait (Springer, 1988). We propose that this second region of productivity results from continuation of the system responsible for production at the shelf break and, further, that the phytodetritus production in this region is transported north through Bering Strait for deposit in the southern Chukchi Sea.
We support the hypotheses presented here with data collected over the last decade from spatially disparate regions of the Bering and Chukchi Seas. This large area is by no means static, being subject to both seasonal and interannual variability. As a result, our interpretation of the data and the model presented are subject to the uncertainty imposed by this variability.

**Methods**

Data was collected during cruises on the R.V. *Alpha Helix* (July 1985 and October 1987) and the R.V. *T.G. Thompson* (July–August 1987) as part of the Inner Shelf Transfer and Recycling (ISHTAR) project. The study area included the regions surrounding St. Lawrence Island in the south to approximately 69°N latitude and from the Alaskan coast in the east to the United States–Soviet Union 1867 Convention Line in the west (Fig. 1). Water column conductivity and temperature were determined with a Neil Brown CTD. A Turner-Designs fluorometer and an acetone extraction procedure.

Fig. 1. A portion of the Bering–Chukchi Shelf, with generalized circulation patterns. The ISHTAR area is designated by the dashed lines. Bering Strait (BS) and modified Bering Shelf water (BSW) are indicated. Anadyr Strait is located between Siberia and St. Lawrence Island (SLI) and Shpanberg Strait is located between St. Lawrence Island and the Alaskan mainland. Arrows do not represent the relative magnitude of current speed.
were used for chlorophyll $a$ analysis (Parsons et al., 1984) on water collected at 5 m depth intervals. Additional water was collected at these depths for automated nitrate analysis (Whitlege et al., 1981). Particulate nitrogen (PN) samples were collected by passing 2.2 liters through precombusted ($450^\circ C$) 0.6 μm quartz filters. The filters were dried at 50°C for 24 h and transported in a desiccator to the laboratory where they were combusted at 800°C for 4 h with approximately 1 g of Cuprox® in evacuated and sealed quartz tubes. PN was determined from the pressure of N$_2$ measured with an MKS Type 122A Absolute Pressure Transducer after breaking the sealed tubes in a high vacuum manifold.

RESULTS AND DISCUSSION

General hydrography of the Bering Sea shelf and slope

The Bering Sea is broadly divided into two regions: the deep Aleutian Basin (>3500 m depth), which accounts for 40% of the area covered by the Bering Sea, and the continental shelf region (<200 m depth), accounting for another 40%. These regions are divided by an approximately 1000 km long shelf break, which has its origins in the

![Diagram of the Bering Sea shelf and slope hydrography](image)

Fig. 2. The cross-shelf advection/diffusion model developed by PROBES investigators which relates the vertical energy distributions to the typical horizontal and vertical property distributions and the fronts, and the inferred freshwater and salt fluxes (from Coachman et al., 1980, with additions).
southwest near Unimak Pass, Alaska, and in the northwest near Cape Navarin, Soviet Union (Fig. 1).

A strong shelf-break front is a persistent feature over the shelf slope (Fig. 2). It separates oceanic water (>32.7 ppt) in the Aleutian Basin from 31.0 to 32.7 ppt shelf water. The geostrophic Bering Slope Current is found on the basin side of the shelf-break front and has an estimated transport of 5 Sv and a speed of up to 10 cm s\(^{-1}\). Long-term mean flow on the shelf side of the front is estimated to be 5 cm s\(^{-1}\) (COACHMAN, 1986).

Shelf water is divided into domains by fronts (Fig. 2) that are closely aligned with specific isobaths (COACHMAN, 1986). To the east is Alaskan coastal water (< 31.0 ppt), which is a mixture of deep Bering Sea water advected onto the shelf near Unimak Pass and fresh river water (KINDER and COACHMAN, 1978). An inner front, found at the 50 m isobath, separates the coastal water from the slowly moving (1 cm s\(^{-1}\)) middle domain. A strongly stratified two-layered system, the middle domain is separated from the outer domain by the middle front located near the 100 m isobath. Finally, the outer domain is separated from the Bering Slope Current by the shelf-break front.

The inner front can be traced to the northwest along the 50 m isobath. At a point south of Shpanberg Strait, the front leaves the 50 m isobath, deviating to the north through Shpanberg and Bering Straits (Fig. 3). The identity of the middle front is lost south of St. Lawrence Island, whereas the shelf-break front can be traced to a point near Cape

Fig. 3. Locations of hydrographic fronts on the Bering Sea shelf (from COACHMAN, 1986).
Navarin where it deviates from the 200 m isobath, turning north towards Anadyr and Bering Straits (COACHMAN, 1986). The upper layer of the Bering Slope Current bifurcates at Cape Navarin and the northern branch is advected across the Gulf of Anadyr and north through Bering Strait as a separate identifiable water mass (here referred to as Anadyr water). Cumulative observational evidence supports the idea that Anadyr water flows northwards across the gently shoaling eastern Bering Sea continental shelf as a western boundary current along the Siberian coast (KINDER et al., 1986).

Throughout summer, the northern extension of the shelf-break front is located in Anadyr Strait and the inner front is found in Shpanberg Strait (Fig. 3). Disappearance of the middle front is the result of the merging of middle and outer domains southwest of St. Lawrence Island, resulting in a water mass referred to as modified Bering Shelf water (Shelf water). The two remaining fronts (shelf break and inner) separate the three water masses that pass through Bering Strait: Alaskan coastal water (<31.5 ppt) to the east, modified Bering Shelf water (31.5–32.8 ppt), and Anadyr water (>32.8 ppt) to the west (these salinity boundaries are not definitive, being subject to variability due to mixing). Long-term average flow in summer through Bering Strait is estimated at 1.1 Sv (COACHMAN and AAGAARD, 1988). Mean current speeds through Bering, Anadyr and Shpanberg straits have been estimated to be 25, 15 and 5 cm s⁻¹, respectively (AAGAARD et al., 1985).

Shelf-break phytoplankton distribution, productivity and transport

The May 1978 areal distribution of Chl a in the southeastern Bering Sea (Fig. 4) demonstrates the presence of a spatially distinct accumulation of plant biomass (100 mg m⁻²) located over the shelf break (IVERSON et al., 1979a). Chlorophyll concentrations were <50 mg m⁻² on both the shelf and basin sides of the shelf-break accumulation and increased to 400 mg m⁻² over the middle shelf, reflecting the presence of the spring bloom (SAMBRONTO et al., 1986).

COACHMAN and WALSH (1981) used a diffusion model to estimate the spring cross-shelf flux of nitrate and its rate of biological uptake in the southeastern Bering Sea during 1976 to 1979. Nitrate uptake rates of approximately 1.0 μg-at. NO₃⁻¹ d⁻¹ were calculated for the 1978 to 1979 spring euphotic zone of the outer shelf domain. Such a nitrate flux would be equivalent to 140 mg NO₃⁻N m⁻² d⁻¹ given a 10 m euphotic zone. If we assume that ammonium flux supports 50% of the nitrogen demand of the phytoplankton (HATTORI and WADA, 1974) and that the C:N assimilation ratio is 6:1, then 1.7 g C m⁻² d⁻¹ would be fixed. During a 120-day growing season, this would result in a summer production of 204 g C m⁻² over the 1000 × 50 km shelf break. GOERING and IVerson (1978) reported production rates of 2.3–5.2 g C m⁻² d⁻¹ at four shelf-break front stations in the southeastern Bering Sea in May 1978.

Vertical profiles of water column characteristics along transect A (Fig. 5), originating in Anadyr Strait and terminating at the shelf break (July 1987), provide insight on the horizontal transport of the plant biomass that had accumulated on the shelf side of the shelf-break front. Some symmetry exists in the water column profiles, particularly salinity and sigma-t, with the apex located near the 75 m bottom depth (Fig. 6). Based on general flow patterns (Fig. 1) described by COACHMAN et al. (1975), it is apparent that the water overlying the >75 m sea bottom flows to the northwest toward Cape Navarin, while the water overlying the <75 m sea bottom spreads to the northeast, through Anadyr Strait, and southeast, south of St. Lawrence Island. Hence, the point on transect A about which
Fig. 4. Distribution of chlorophyll $a$ (mg m$^{-2}$) in the southeastern Bering Sea in May 1978 (redrawn from IVERSON et al., 1979a).

Fig. 5. Locations of transects (solid lines) and the U.S.–U.S.S.R. 1867 Convention Line (dotted line).
Fig. 6. Vertical cross-sections from transect A in July 1987. Arrows indicate the approximate point about which the flow rotates on this transect. The transect originates in Anadyr Strait (AS) and terminates at the shelf break (SB).

The northern extension of the Bering Slope Current rotates (marked by an arrow in Fig. 6) is the 75 m depth. The very cold temperature at this point (<-1.5°C) suggests that the origin of this central pool is winter-cooled water (COACHMAN et al., 1975) that is not easily displaced (Fig. 6). The northern extension of the Bering Slope Current (>32.7 ppt Anadyr water) crosses the Gulf of Anadyr and continues through Anadyr Strait. Chlorophyll a accumulation is evident above the front at the shelf break, with the maximum concentration increasing from 10 mg m^-3 over the shelf break to >20 mg m^-3 south of Anadyr Strait (Fig. 6).

Based on salinity and nitrate distributions from transect F (Fig. 5), it appears that following bifurcation at Cape Navarin, the main flow of Anadyr water is located over the 70 m isobath (Fig. 7). The salinity profile broadly locates Shelf water above the 90 m isobath. Near the coast in the Gulf of Anadyr, salinity is >34.0 ppt, a value not in character with Anadyr water. It is likely that the coastal water is residual from winter, as indicated by a very low near-bottom temperature (-1.6°C) and reduced nitrate concent-
trations (Fig. 7). The highest nitrate values overlie the 70 m isobath, suggesting that this isobath lies beneath the main flow line.

The areal distribution of chlorophyll south of St. Lawrence Island (Fig. 8) reveals that bifurcation of Shelf water occurs at the west end of St. Lawrence Island. A portion of Shelf water plant biomass enters Chirikov Basin (the region north of St. Lawrence Island

Fig. 7. Vertical cross-sections from transect F in August 1970 (profiles drawn from data of HUFFORD and HUSBY, 1970). The transect originates in the northwestern Gulf of Anadyr (NW) and terminates to the southeast (SE).

Fig. 8. Areal distribution of chlorophyll a (mg m⁻²) along transect A and presumed circulation in July 1987. Chlorophyll isolines are drawn according to presumed direction of flow.
and south of Bering Strait; Fig. 1) via Anadyr Strait, with the remainder flowing to the east, south of St. Lawrence Island. A portion of that plant and detrital material transported south of the island transits the western end of Shpanberg Strait. Further evidence for bifurcation at St. Lawrence Island exists in transects B (Fig. 9) and D (Fig. 11), across Anadyr and Shpanberg Straits, respectively, and transect C (Fig. 10), located on the south side of the island (July 1985). Anadyr water was present in all transects (Figs 9-11), as evidenced by the presence of >32.7 ppt salinity. During transit south of St. Lawrence Island, the maximum chlorophyll concentrations in Anadyr water increased from approximately 1 mg m$^{-3}$ (Fig. 9) to 5–11 mg m$^{-3}$ (Figs 10 and 11) while the maximum nitrate concentration was reduced by 21 µg-at. N l$^{-1}$. Biological removal and mixing of the water column are two mechanisms by which the nitrate concentration could be reduced significantly during transit. Though we do not know the extent of mixing for the bulk of Anadyr water, mixing must have been negligible where high salinity values were not significantly reduced during transit. Given a mean annual current speed of 5 cm s$^{-1}$ to the east (Tripp, personal communication), approximately 44 days are necessary for the water to flow the length of St. Lawrence Island. This implies a mean nitrate utilization rate of approximately 0.02 µg-at. NO$_3$-N l$^{-1}$ d$^{-1}$ in water that did not undergo mixing. This rate is comparable to the rate of nitrate uptake measured in the western end of Shpanberg Strait (Hansell and Goering, submitted). Because there is no evidence of chlorophyll accumulation subsequent to flow past transect C, plant production resulting from nitrate uptake must be grazed in the water column or lost to the benthos. Both loss terms are likely but the relative importance of each is unknown.
Fig. 10. Vertical cross-sections from transect C in July 1985. The transect originates at St. Lawrence Island (SLI) and terminates south of the island.

Fig. 11. Vertical cross-sections from transect D in July 1985. The transect originates at St. Lawrence Island (SLI) and terminates near the Alaskan coast (AK).
Transit through Anadyr and Shpanberg Straits

Throughout the summer season, most plant material transported through Anadyr and Shpanberg Straits is found within the salinity envelope that defines Shelf water (31.5–32.7 ppt). The general summer distribution of bottom salinity provides a view of the path taken by Shelf water (Fig. 12). To trace the plant material that is produced south of St. Lawrence Island and transported into the area, Chl a concentrations were integrated from below the approximate depth of the pycnocline (15 m) to the bottom, thus excluding plant material locally produced at the surface. It is clear that the Chl a concentration (integrated from 15 m to the bottom) outlines the same path as the Shelf water salinity envelope (Fig. 13). Plant material within Shelf water is transported through the straits throughout the summer season (Fig. 14), decreasing in concentration by mid-October. It is likely that transport of phytodetritus begins in late May or early June, when shelf-break production is initiated (Fig. 4).

Deposition and regeneration in the northeastern Bering Sea

The Shelf water chlorophyll signal can be traced north across the Chirikov Basin and eventually through Bering Strait (Fig. 13). During its transit across the basin, large amounts of plant biomass must fall to the sediment as the source of carbon required by the rich amphipod beds found in the region. GREBMEIER et al. (1988) report a mean benthic biomass of 20.2 g C m⁻² under Shelf water in the northern Bering Sea (10¹¹ m⁻²),

Fig. 12. Distribution of bottom salinity (ppt) in July 1987.
Fig. 13. Distribution of chlorophyll $a$ (mg m$^{-2}$) integrated from 15 m to the bottom (July 1987).

Fig. 14. Vertical cross-sections of chlorophyll $a$ (mg m$^{-3}$) in Anadyr and Shpanberg Straits on four dates in summer 1987.
mostly dominated by detritus feeding amphipods, and GREBMEIER and McRoy (1989) estimate mean benthic organic carbon mineralization rates from July to September (1984–1986) to be 19.5 mmol C m^{-2} d^{-1}.

The rate of carbon mineralization is estimated to be equivalent to a PN sedimentation flux of 38 mg N m^{-2} d^{-1}, given an average C:N ratio (by weight) of 6.2 for the particulate fraction in Shelf water (GREBMEIER, 1987). Assuming a 20% transfer efficiency in the benthos (WALSH, 1988), 47 mg N m^{-2} d^{-1} are required to meet the measured mineralization rate. PN can be expressed as Chl a concentration using a linear regression equation that describes the proportion of PN (µg-at. N l^{-1}) to Chl a (mg m^{-3}). For Shelf water Chl a below the pycnocline, PN = 0.542 (Chl) + 1.338 (r^2 = 0.88, df = 173). Therefore, approximately 3.1 \times 10^8 g Chl a d^{-1} must be available to meet the carbon demands of the benthos. WALSH et al. 1989 have estimated the mean Shelf water Chl a concentrations in 1987 to be 97 and 80 mg m^{-2} in Anadyr and Shpanberg Straits, respectively. Average summer transport was estimated from current meter data to be 0.87 and 0.31 Sv in the respective straits. The average depth of Shelf water in each strait is approximately 35 m, and we assume that Shelf water contributes approximately 30% of the total flow through each strait. From this, we calculate the mean flux of Shelf water chlorophyll through the straits to have been 0.8 \times 10^8 g Chl a d^{-1}. Given the chlorophyll equivalent of benthic carbon consumption calculated above, the flux of biomass through Anadyr and Shpanberg Straits in 1987 could have met approximately 26% of the daily carbon requirements of the Chirikov Basin benthos. Fukuchi (personal communication) has estimated from sediment trap data the rates of organic matter deposition in the Chirikov Basin (1988) to have been approximately 500 mg C m^{-2} d^{-1} and 70 mg N m^{-2} d^{-1}.

In July 1987, maximum Shelf water chlorophyll concentrations were <200 mg m^{-2} when transiting Anadyr and Shpanberg Straits and increased to >600 mg m^{-2} over the Chirikov Basin (Fig. 13). The benthic amphipods are subsisting in part on the plant and detrital materials transported into the area with Shelf water and, in turn, are remobilizing nitrogen (ammonium and urea) from the particulate fraction (LUND and Blackburn, personal communication), thus stimulating new plant growth.

**Surface blooms in the ISHTAR study area**

*East bloom.* Because the Shelf water bottom chlorophyll mass is mixed below the halocline to the bottom, it is, to some extent, light limited (HANSSELL and GoERING, submitted). Though Shelf water is often capped by low salinity water (except in regions of very close proximity to St. Lawrence Island) as it enters the ISHTAR study area, it can be found near the surface north of the island. Where Shelf water is near-surface (<15 m depth), significant accumulation of Chl a may be found (Fig. 15, Sta. 42). This surface accumulation is here referred to as the east bloom. The east bloom is clearly a surface extension of the phytodetritus within Shelf water (Fig. 15, Sta. 43) that has been transported through Anadyr and Shpanberg Straits. The east bloom is relatively narrow (10 km), originating north of St. Lawrence Island and terminating (see below) in the Bering Strait, with a surface area of approximately 500–1000 km² (Fig. 16). Hourly nitrogen productivity during August 1987 ranged from 1.20 to 2.52 mg-at. N m^{-2} h^{-1}, with a mean of 1.8 mg-at. N m^{-2} h^{-1} (HANSSELL and GoERING, submitted).

*West bloom.* As discussed above, Anadyr water is continuously upwelled into the ISHTAR study area through Anadyr Strait. It is cold, high salinity water (>32.7 ppt) characterized by high nitrate concentrations (>25 µg-at. N l^{-1}). Immediately north of
Summer phytoplankton production

Fig. 15. Vertical cross-sections from transect E in July 1987. The transect originates at the U.S.-U.S.S.R. Convention Line (CL) and terminates near the Alaskan coast (AK).

Fig. 16. Distribution of chlorophyll a (mg m\(^{-2}\)) integrated from the surface to 15 m. The east (EB) and west (WB) blooms are indicated.
Anadyr Strait, Anadyr water often can be found well mixed from surface to bottom. Further north of the strait, Anadyr water typically is overlain by Shelf water or Siberian coastal water.

Where Anadyr water remains well mixed to the surface, no surface bloom has been found to develop (Fig. 15, Stas 37-39). This is because the plant cells, though well supplied with nutrients, are probably mixed out of the euphotic zone at a frequency preventing significant net production (Sverdrup, 1953). Chlorophyll concentrations in the highest salinity Anadyr water do not attain high levels south of Bering Strait. Only where near-surface Anadyr water is capped by low salinity water (<32.0 ppt), thus providing the requisite stability for bloom production in the overlying water (Fig. 17, Sta. 56), are blooms found. Because of the high concentration of nitrate in Anadyr water, a nitrate concentration differential of >20μg-at. N L⁻¹ exists between Anadyr water and the overlying low nutrient, low salinity water. The resulting gradient must support diffusive export of nitrate into the surface lens. Hence, at the pycnocline, enhanced plant production can be found (McRoy et al., 1987). Where capping of Anadyr water was followed by bloom development, the greatest rate of plant production and the greatest surface (0-15 m) concentrations of plant biomass (here referred to as the west bloom) were measured in 1987 (Fig. 16). Hansell and Goering (submitted) have estimated that approximately 60% of annual productivity in the west bloom is transported into the southern Chukchi Sea to be deposited in the sediments.

Chlorophyll distribution and primary production in the west bloom has been measured from 1985 to 1987 (Springer, 1988). Carbon uptake rates measured within the west bloom.
bloom ranged between 1 and 16 g C m\(^{-2}\) d\(^{-1}\), while outside the west bloom rates were usually less than 1 g C m\(^{-2}\) d\(^{-1}\). The area south of Bering Strait that was defined as the west bloom averaged \(0.87 \times 10^{10}\) m\(^2\). The average daily production for the west bloom was estimated to range from 1.5 to 5.4 g C m\(^{-2}\) d\(^{-1}\), with a mean of 2.7 g C m\(^{-2}\) d\(^{-1}\). This is equivalent to mean production in the east bloom; however, the west bloom is estimated to be approximately 9–18 fold greater in surface area than the east bloom.

Still higher production would be anticipated following transit of the west bloom through Bering Strait into the southern Chukchi, where surface chlorophyll concentrations (0–15 m) of >800 mg m\(^{-2}\) can be found, and carbon production as high as 16 g C m\(^{-2}\) d\(^{-1}\) has been reported (SPRINGER, 1988). Unfortunately, the west bloom is often not available for direct observation during passage through Bering Strait due to the limitations set by the U.S.–U.S.S.R. 1867 Convention Line. The east bloom, too, flows northwest across the convention line into Soviet territory at Bering Strait and becomes unavailable for direct observation. Where the west bloom re-enters American territory north of Bering Strait, the east bloom is no longer in evidence, suggesting that the two blooms have merged (Fig. 16). The distribution of east and west bloom chlorophyll is readily visible in a Coastal Zone Color Scanner image available in WALSH et al. (1989, their Fig. 19). The merged bloom, along with the Shelf water bottom chlorophyll that has transited Bering Strait, must be a significant source of carbon for the rich benthic populations found in the southern Chukchi Sea (STOKER, 1981; GREBMEIER et al., 1988, 1989; HANSSEL and GOERING, submitted).

It should be noted that the position and extent of the west bloom is highly variable. Being a near-surface phenomenon, its position is determined in large part by the pattern and strength of the local winds. Hence, the west bloom is not present on transect E (Fig. 15) in July 1987, while approximately one month later at the same position, the bloom is present (Fig. 16).

**CONCLUSION**

*General model for summer production and consumption on the northeastern Bering Sea shelf*

A general model for the production and fate of phytoplankton during summer in two regions over the continental shelf of the Bering Sea is presented in Fig. 18. We propose that both regions of productivity are supported by nutrients transported into the area with the Bering Slope Current and that the fate of the phytodetritus produced is significantly affected by advection. Our hypothesis is that the system supporting primary productivity in the ISHTAR area (i.e. the west bloom) is the downstream continuation of the system supporting primary productivity at the shelf break of the Bering Sea.

Significant plant production takes place at the Bering Sea shelf-break front and the same system of production continues into the northern Bering Sea as part of the modified Bering Shelf water mass. Production at the shelf-break front probably begins in May, when water column stability maintains a light regime favorable for plant growth, and continues into the autumn, when frequent wind mixing and cooling of the surface water column reduces net plant production. Productivity associated with the shelf-break front is estimated at approximately 200 g C m\(^{-2}\) over the 120-day growing period. Near-bottom chlorophyll concentrations are <1 mg m\(^{-3}\) (Fig. 6) and sinking rates of phyto-
plankton are estimated to be 1 m d\(^{-1}\) at the shelf-break front (Iverson et al., 1979b). Consequently, shelf-break production is diverted directly to the pelagic food web of the outer shelf domain throughout the summer.

The Bering Slope Current bifurcates at Cape Navarin and the northern branch, now referred to as the Anadyr Current, crosses the Gulf of Anadyr, passing north through Anadyr and Bering Straits. The shelf-break front, along with the systems of productivity associated with it, is diverted to the north with the Anadyr Current. At St. Lawrence Island the system bifurcates with a portion of the phytodetritus transiting Anadyr Strait and the remainder moving east, south of the island. The plant biomass transported around the island in 1987 (i.e. the deep chlorophyll layer) was estimated to supply 26% of the daily organic carbon demand of the rich amphipod beds located in the Chirikov Basin, south of Bering Strait. During shoaling of modified Bering Shelf water from the shelf break (200 m) to Chirikov Basin (<50 m), a transition is made from a predominantly pelagic food web to one that is directly tied to the benthos. This is reflected in a significant increase in benthic biomass with increasing latitude in the region (Stoker, 1981).

The Anadyr Current, meanwhile, shoals at the shallow Anadyr Strait and an intense surface bloom (i.e. the west bloom) develops north of the strait as a result of the sudden
influx of nitrate to the euphotic zone. The west bloom is advected to the north through Bering Strait, where it is joined by the east bloom, to be deposited in the sediments of the southern Chukchi Sea.

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