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Spatial patterns of primary production on the shelf, slope and basin of the Western Arctic in 2002

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Abstract

In the spring and summer of 2002 primary production in the Chukchi Sea was measured, using ^{14}C uptake experiments. Our cruise track encompassed the shelf and continental slope area of the Chukchi and Beaufort Seas progressing into deep water over the Canada Basin. The study area experienced upwards of 90% ice cover during the spring, with ice retreating into the basin during the summer. Production in the spring was light-limited due to ice cover, with average euphotic zone production rates of $<0.3\,g\,C\,m^{-2}\,d^{-1}$. Values of $8\,g\,C\,m^{-2}\,d^{-1}$ were observed in association with surface bloom conditions during the initial ice breakup. Considerable nutrient reduction in the surface waters took place between the spring and summer cruise, and although not observed, this was attributed to a spring bloom. Decreased ice cover and increased clarity of surface waters in the summer allowed greater light penetration. The highest rates of production during the second cruise were found at 25–30 m, coincident with the top of the nutricline. Daily euphotic zone productivity in the summer averaged $0.78\,g\,C\,m^{-2}\,d^{-1}$ on the shelf and $0.32\,g\,C\,m^{-2}\,d^{-1}$ on the edge of the Canada basin. These data provide an estimated annual production of $90\,g\,C\,m^{-2}\,yr^{-1}$ in the study area.

Keywords: Primary productivity; Chukchi Sea; Arctic Ocean

1. Introduction

The shelf seas of the Arctic Ocean comprise roughly 50% of the total area and account for 25% of the global sum. Current estimates put their combined primary productivity (PP) at $279\,Tg\,yr^{-1}$ (Sakshaug, 2004), which is over 80% of PP observed above 65°N. Due to ice cover and the polar night, extreme seasonality is observed in PP. The growing season is <150 days, and the duration reduces with increasing latitude (Springer and McRoy, 1993).

Physical, chemical and biological characteristics of the Chukchi Sea are strongly influenced by the northward flow of water through the Bering Strait, which is driven by sea level difference (Woodgate et al., 2005). This advective regime is strongest in the summer (Weingartner, 1997; Coachman and Aagaard, 1988), supporting a highly productive region on the edge of the largely oligotrophic Arctic basin (McRoy, 1993). Ice cover in the Chukchi and Beaufort Seas varies from moderate seasonal ice cover in the south, to extensive multiyear ice towards the north. Satellite images show that ice

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cover persists in the area from November through April/May (Parkinson et al., 1987; Gloersen et al., 1992). Chlorophyll biomass in the area is greatly reduced by ice cover in the spring, but intense blooms are observed with ice edge retreat (Wang et al., 2005). These conditions drive the strong seasonality that is observed in biological processes in the Chukchi and Beaufort Seas. Observations of Barrow Canyon which is located in the northeast corner of the Chukchi Sea have identified it as an extremely dynamic location. Cross-sectional variability is evident, with northward currents of up to 10–20 $cm\,s^{-1}$ in the summer. In addition episodic wind-driven upwelling of Atlantic-derived water from below the permanent pycnocline in the Arctic basin up into the Canyon has been observed (Woodgate et al., 2005).

Logistical difficulties due to heavy ice cover mean that previous studies of PP in this area have been focused on summertime production. Those rates that have been measured indicate that the Chukchi Sea region just north of the Bering Strait has some of the highest PP rates observed in the Arctic at $\sim$15 $g\ C\,m^{-2}\,d^{-1}$ (Springer and McRoy, 1993). During August of 1993 average euphotic zone integrated production rates of 0.30 ± 0.08 $g\ C\,m^{-2}\,d^{-1}$ were measured in the northwest Chukchi Sea (Cota et al., 1996). In their E transect, located over Hanna Shoal into the Canada Basin, integrated euphotic zone production was 0.75 $g\ C\,m^{-2}\,d^{-1}$ on the shelf and 0.12 $g\ C\,m^{-2}\,d^{-1}$ over the basin. In comparison during the 1994 Arctic Ocean Section cruise primary production was measured as high as 2.57 $g\ C\,m^{-2}\,d^{-1}$ on the Chukchi shelf at the end of July (Gosselin et al., 1997) and decreasing to $<$0.1 $g\ C\,m^{-2}\,d^{-1}$ once over the basin. Concentrations of nitrate were high in July of 1994, while in August of 1993 nitrate was observed to be much lower in the surface waters. Cota et al. (1996) concluded that they had missed the spring bloom and were observing conditions symptomatic of a post-bloom environment. Ice algal production, although not often studied, has been estimated be responsible for up to 3% of total production on shelf areas (Gosselin et al., 1997).

In the spring and summer of 2002 the Western Arctic Shelf Basin Interaction program (SBI) provided an opportunity to measure water-column productivity during the spring when the only ice-free area was Barrow Canyon and the summer when the Chukchi shelf is largely ice-free. Here we discuss the temporal and spatial variation in productivity in the study area and environmental factors influencing photosynthesis.

2. Methods

2.1. Sampling procedures

Nutrient and oxygen concentrations, along with a full suite of hydrographic measurements, were determined throughout the water column for 39 stations in the spring cruise (10 May to 12 June 2002) and 45 stations during the summer (19 July to 21 August 2002). These were taken in accordance with WOCE/JGOFS protocols and outlined in Codispoti et al. (2005). Chlorophyll measurements were also made at all hydrographic stations using standard fluorometeric techniques outlined in Hill et al. (2005). Carbon fixation was measured in surface waters ($<$90 m) at selected stations between 7 and 9 a.m. (ship time), with additional chlorophyll samples taken in parallel. Routine sampling at productivity stations included continuous vertical profiles of temperature, salinity and fluorescence with a Sea Bird 911 CTD (conductivity, temperature, depth) profiler and fluorometer. Discrete samples were collected in 30-l Niskin bottles for chlorophyll and productivity measurements. Optical depths for productivity were estimated with the Secchi disk (Holmes, 1970) and corresponded to 80–100%, 50%, 30%, 15%, 5% and 1% of surface irradiance. These depths are consistent with in situ irradiance measurements collected after the productivity cast using a Satlantic free-falling profiling 13-channel radiometer.

2.2. Primary production

PP was measured by ^{14}C (carbon) uptake fixation with simulated in situ (SIS) incubations. Isotope stocks were prepared according to the recommendations of Fitzwater et al. (1982). Our SIS incubator had neutral density and/or blue plastic filters to simulate in situ irradiance spectra at depths consistent with sample collection. Incubators were set up with a flow-through system of surface seawater. Samples were placed in 280 ml polycarbonate bottles and inoculated with 370 kBq $^{14}C\text{-}NaHCO_3$ and incubated for 24 h. Total activity added and particulate adsorption were measured at time zero in parallel samples. Particulate material was harvested on 25 mm Whatman GF/F filters and rinsed with 5–10 ml of 0.01 N HCl in filtered seawater to remove inorganic carbon. Radioactivity was assayed by liquid scintillation counting and corrected for particulate adsorption at time zero, background and counting efficiency. Water temperature in the incubator and incident photosynthetically active radiation (I_0 PAR = 400–700 nm) above the incubator were measured continuously with a Licor model 1000-15 thermistor and Licor model SA-190 cosine collector, respectively. Both variables were recorded at 5 min intervals with a Licor model L1-1000 data logger.

Technical difficulties with the shipboard seawater flow through system necessitated the use of a refrigerated van system to cool water and the forward ballast tanks to store water. These activities were outlined in the appendix to the cruise report which is available at: www.joss.ucar.edu/sbi/.

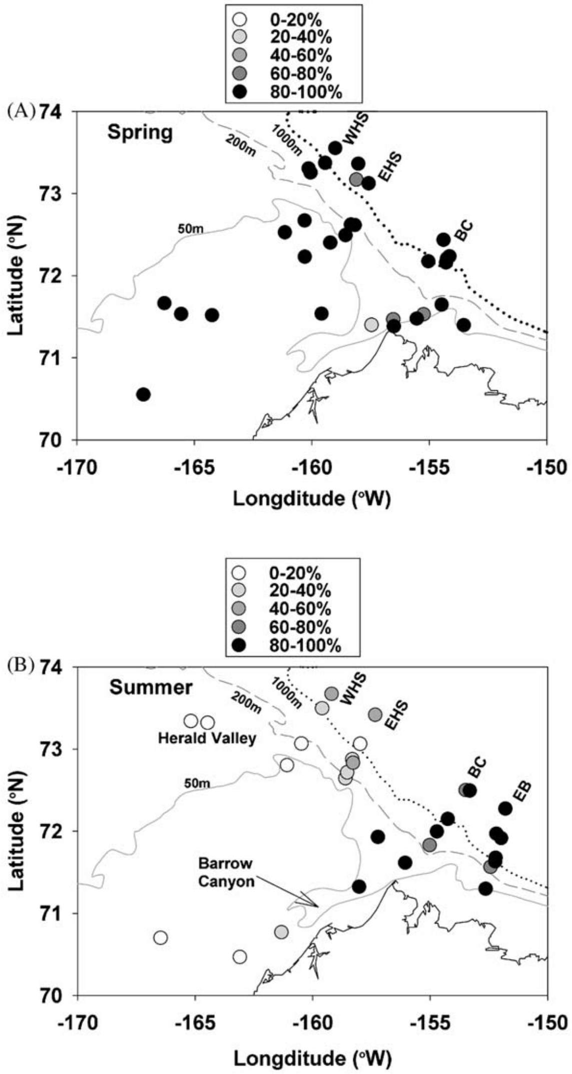

Fig. 1. (A, B) Percentage visible ice cover at experimental stations during the spring and summer cruises 2002. Spring data supplemented by ice observers R. Gradinger, H. Eicken and J. Tapp, of the University of Alaska, Fairbanks. Transects are labeled West Hanna Shoal (WHS), East Hanna Shoal (EHS), Barrow Canyon (BC) and East of Barrow (EB). Bathymetry is indicated as follows, solid line 50 m, dashed line 200 m and dotted line 1000 m.

2.3. Chlorophyll

Total chlorophyll *a* (Chl *a*) was determined fluorometrically (Holm-Hansen et al., 1965) by filtration through 25 mm Whatman GF/F filters. The filters were placed in vials on ice, sonicated in 90% acetone, and extracted for 24 h. Extracted fluorescence was measured before and after acidification (10% HCl) with a Turner Designs model AU-10 fluorometer calibrated with commercially purified Chl *a* (Turner Designs).

3. Results

3.1. Physical characteristics of study area

In the spring and summer of 2002, two cruises were undertaken in the Chukchi Sea as part of the Western Arctic Shelf Basin Interactions project. The first of these cruises took place from 10 May to 12 June and will be referred to as the spring cruise. During this time, ice cover in the study area was heavy with a mixture of seasonal to multi-year ice. Observations taken at each experimental station estimated ice cover to be >80% (Fig. 1A), with floes up to 1–2 m thick in places with a covering of snow. Towards the end of the spring cruise ice cover started to retreat from the area, becoming thinner and characterized by melt ponds and lack of snow cover. Reduced ice cover was observed at the head of Barrow Canyon, which was sampled in mid-June (Fig. 1A). The second cruise took place from 19 July to 21 August and will be referred to as the summer cruise. At the start of the cruise ice cover had retreated to the slope leaving the shelf area largely free of ice (Fig. 1B). The Barrow Canyon area was sampled in July, ice cover was observed to be over 50% and characterized by partially melted and fragmented ice which was under continual movement. In the western extent of the study area sampled during August, ice cover was <50% and ice floes were observed to be fragmented and partially submerged.

Three transects were run during the spring, identified and labeled as follows: West Hanna Shoal (WHS), East Hanna Shoal (EHS), and Barrow Canyon (BC). During the summer these were reoccupied with the addition of a further transect east of Barrow Canyon (EB), which could not be reached in the spring due to heavy ice cover (Fig. 1A and B). The upper ~150 m of the water column in the study area, which encompasses the maximum depth of productivity measurements, are dominated by the Pacific-water signal (Codispoti et al., 2005). Nitrate can be low ($<0.5\,\mu$M) even before the seasonal onset of productivity. The WHS and EHS transects progress from the shelf (<50 m depth) to over 3000 m depth. A strong shelfbreak jet has been observed flowing eastwards across these transects carrying comparatively higher-nutrient Pacific water (Pickart, 2004). The authors refer readers to the following papers for a more comprehensive discussion of the physical and chemical environment (Codispoti et al., 2005; Pickart, 2004; Woodgate et al., 2005).

3.2. Net daily production values

Net daily production integrated over the euphotic zone from six light depths was calculated for each experimental station. During the spring, production was observed to be uniform $<0.3\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ in the study area, with little spatial variation. The head of Barrow Canyon was the one exception to this with a daily production rate of $8\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$. This was associated with a reduction in ice cover, indicating the start of a spring bloom (Fig. 2A). This bloom rate is similar to those observed further south in the well-documented highly productive areas of the Chirikov Basin and Bering Strait (Springer and McRoy, 1993). The spring productivity values correspond to euphotic zone integrated chlorophyll concentrations of $<0.05\,\mathrm{g\ Chl\,m^{-2}}$ (Fig. 3A). Increased chlorophyll of $\sim1.5\,\mathrm{g\ Chl\,m^{-2}}$ was associated with the high production observed at the head of Barrow Canyon. Average production rates excluding the one high value in Barrow Canyon were 0.164 and $0.110\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$ for the shelf and basin, respectively.

During the summer, a spatial variation of two orders of magnitude was observed in productivity rates, with values ranging from $0.08\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$ at some basin locations to $2.90\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$ on the shelf break (see Fig. 2B). A peak in productivity at the head of Barrow Canyon was again observed. Productivity values observed at stations with bottom depths over 200 m in the canyon are approximately double that of stations with similar bathymetry at the EHS and WHS transects. Chlorophyll biomass was marginally increased over spring values (Fig. 3B), with chlorophyll over 0.1 g $\mathrm{Chl\,m^{-2}}$ linked with heightened ($2\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$) production at Herald Valley. Average production rates increased, with $0.783\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$ on the shelf similar to summer 1993 observations (Cota et al., 1996) and $0.324\,\mathrm{g\ C\,m^{-2}\,d^{-1}}$ over the basin.

3.3. Vertical profiles of chlorophyll, production, and specific production

Mean profiles through the euphotic zone show that during the spring, chlorophyll biomass was highest in surface waters, with values on average $0.6\,\mathrm{mg\,m^{-3}}$ (Fig. 4), decreasing with increasing optical depth to $<0.1\,\mathrm{mg\,m^{-3}}$ at the 1% light level. The maxima for primary production and biomass specific production were both observed below the chlorophyll maxima at 10–15 m. The high productivity station in Barrow Canyon was not included in the plot as it biased the results. However, the productivity maximum at this Barrow Canyon site was observed at 2 m with a value of 45 mg $\mathrm{C\,m^{-3}\,h^{-1}}$ and a peak in biomass specific productivity of $4.1\,\mathrm{mg\ C\,mg\ Chl^{-1}\,h^{-1}}$ was observed at the same depth. Chlorophyll was $11\,\mathrm{mg\,m^{-3}}$ throughout the water column.

The summer data showed strong subsurface maximum in chlorophyll biomass exceeding $2\,\mathrm{mg\,m^{-3}}$ on average (Fig. 4) and reaching as high as $40\,\mathrm{mg\,m^{-3}}$ on the WHS transect (Fig. 3B). This chlorophyll maximum was situated at a depth of 25 m corresponding to 5% of surface light. Chlorophyll at the surface was found in concentrations below $0.5\,\mathrm{mg\,m^{-3}}$. The maximum in productivity occurred in association with the maximum measured chlorophyll. Values on average show a sevenfold increase over the spring, at $\sim1.4\,\mathrm{mg\ C\,m^{-3}\,h^{-1}}$. The highest rates were observed in Barrow Canyon, $8\,\mathrm{mg\ C\,m^{-3}\,h^{-1}}$ and at the shelf break of WHS and HV, 2–6 $\mathrm{mg\ C\,m^{-3}\,h^{-1}}$. Biomass specific production peaks were observed at both the surface and subsurface. However, there was no strong relationship between production and biomass specific production. Observed summer values were approximately double that of spring specific productivity. The highest specific productivity was associated with the high chlorophyll and production station on the WHS transect.

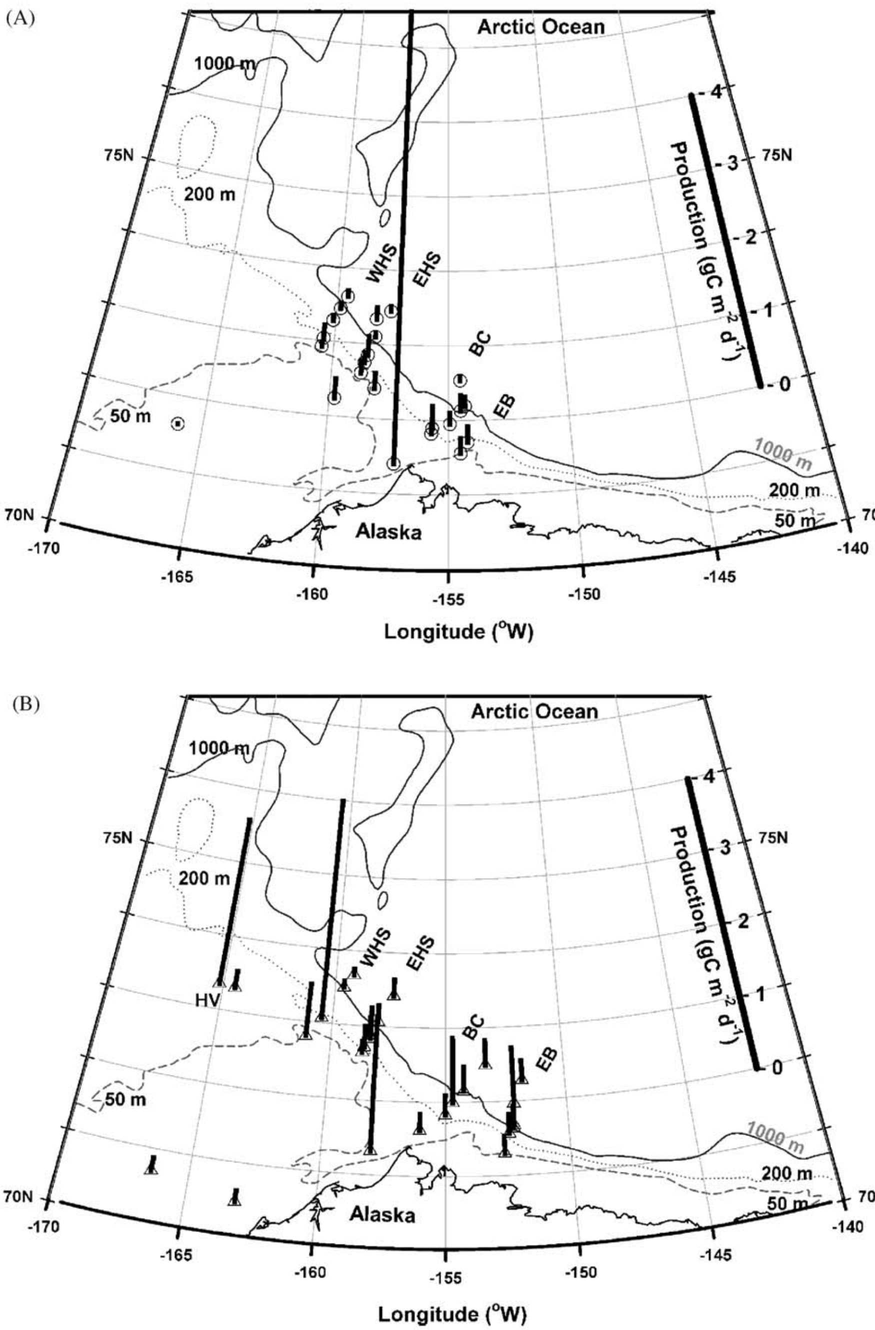

Fig. 2. Euphotic zone integrated net daily production: (A) Spring 2002 (05/08/02–06/12/04) and the cruise track progressed from WHS through EHS to BC. (B) Summer 2002 (07/18/02–08/21/02), cruise track started on BC transect and proceeded through EB, EHS, WHS and HV. Transects are labeled West Hanna Shoal (WHS), East Hanna Shoal (EHS), Barrow Canyon (BC), East of Barrow (EB), and Herald Valley (HV).

Fluorescence profiles from the CTD mounted instrument indicated an average peak at 31 m in the summer (not shown). This result would imply that at times productivity and chlorophyll measurements were not made at the true chlorophyll maxima. As such it would be premature to suggest that the peak in productivity occurs at the pigment maximum, previous observations having placed it just above this depth (Cota et al., 1996).

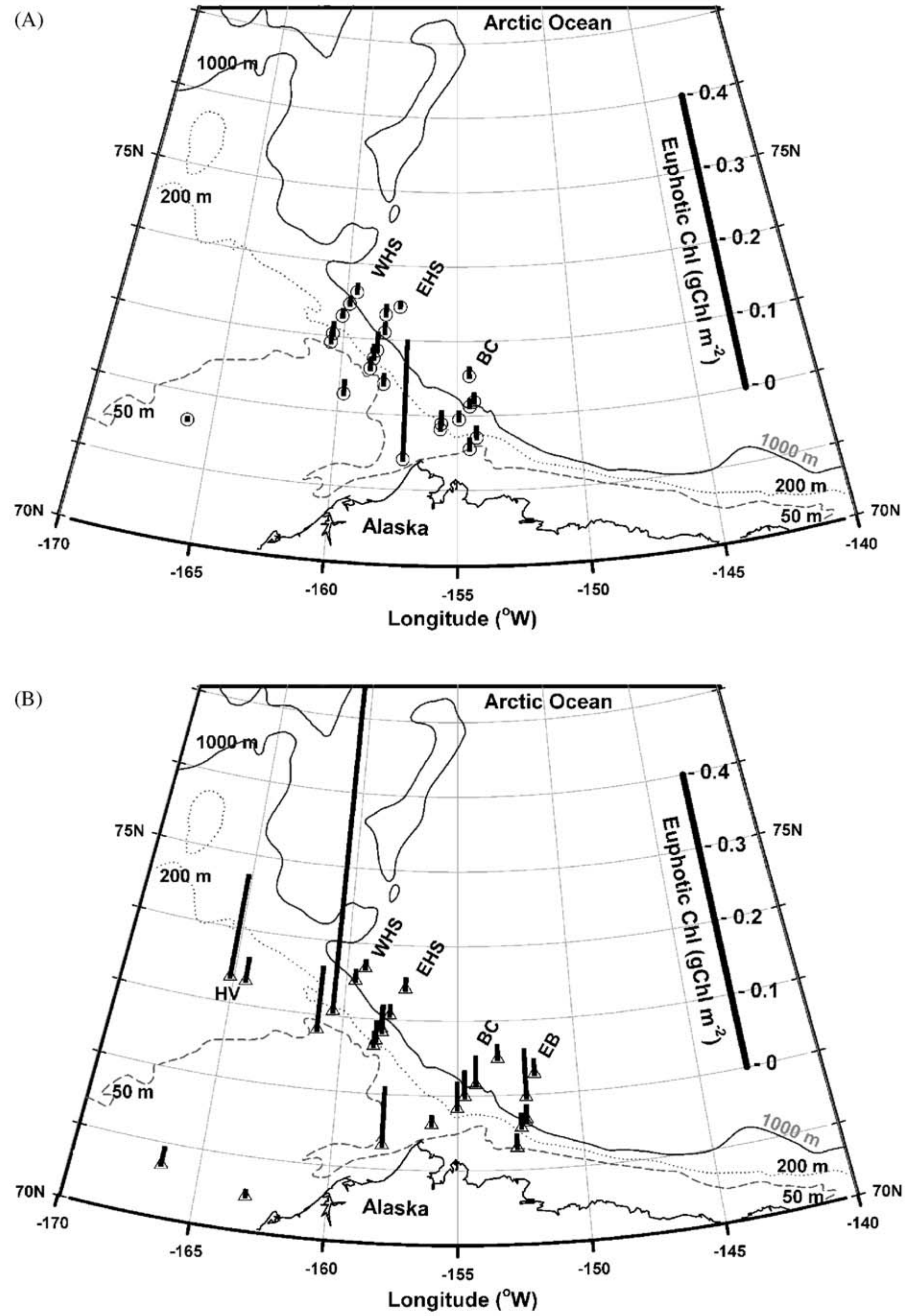

Fig. 3. Euphotic zone integrated chlorophyll: (A) Spring 2002 (05/08/02–06/12/04), cruise track progresses from WHS through EHS to BC. (B) Summer 2002 (07/18/02–08/21/02), cruise track started on BC transect, through EB, EHS, WHS, and HV. Transects are labeled West Hanna Shoal (WHS), East Hanna Shoal (EHS), Barrow Canyon (BC), East of Barrow (EB), and Herald Valley (HV).

3.4. Environmental forcing of photosynthesis

The EHS transect was chosen for further investigation due to its high resolution and representation of a typical shelf to basin transition in the Chukchi and Beaufort Seas. Barrow Canyon, although a site of high production and a focused conduit for shelf to basin export of carbon, is atypical of general processes of shelf–basin exchange (Weingartner, 1997). Maximal primary

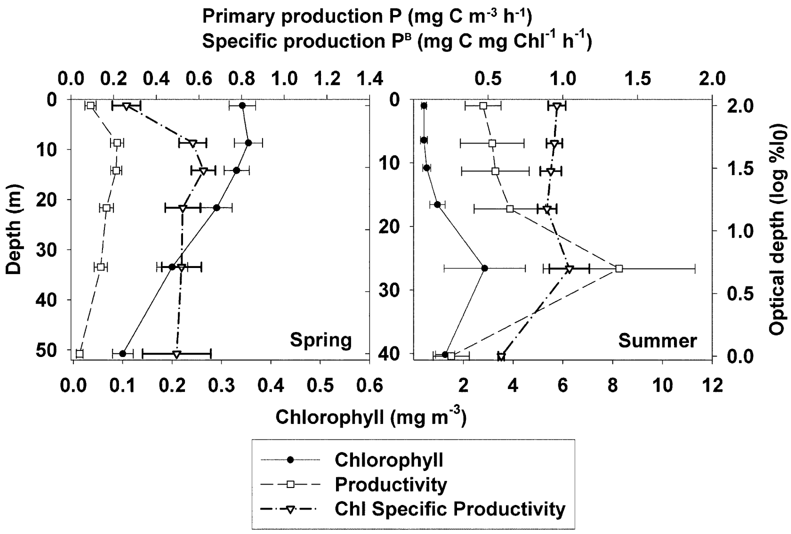

Fig. 4. Vertical distributions of chlorophyll *a*, primary production and biomass-specific production during the spring and summer of 2002 at experimental stations in the study area. Production estimates are based on 22–26 h incubations. The one high productivity station during the spring was not included as it biased results. Values shown are means ± 1SE. Chlorophyll data supplied by Dean Stockwell of the University of Alaska, Fairbanks.

production on the shelf during the spring was observed at ~15 m depth (Fig. 5A), with values approaching 0.3 mg C m^{-3} h^{-1}. This subsurface maxima in production extended over the shelf break and into the basin with reduced values. Chlorophyll biomass at this time was greatest in the surface 10 m (Fig. 5B). Nitrate reached 6 μM L^{-1} in the production maximum, dropping below 2 μM L^{-1} over the basin (Fig. 5C). Oxygen was under saturated on the shelf (Fig. 5D), assuming a concentration of 385 μM at 100% saturation, while in the basin supersaturation was observed. Analysis of size-fractionated production reveals that upwards of 50% of production was observed to take place in particles with diameters over 5 μm (Fig. 5E). At the productivity maximum this increased to 70% in particles over 5 μm.

Production in the summer was elevated compared to the spring, reaching 0.6 mg C m^{-3} h^{-1} at ~30 m, and was associated with the subsurface chlorophyll maximum (Fig. 6A and B). Chlorophyll concentrations at this depth reached 10 mg m^{-3} on the shelf, declining to <1 mg m^{-3}over the basin. Production was observed to decrease to 0.2 mg C m^{-3} h^{-1} in the basin in parallel with this. Nitrate in the surface 10 m underwent significant reduction from the spring to <1 μM L^{-1}. Nitrate concentrations increased with depth through a steep gradient from 12 to 30 m on the shelf (Fig. 6C). At the bottom of the euphotic zone ~40 m nitrate concentrations had increased compared to the spring. Basin concentrations of nitrate at the surface were reduced compared to both the shelf and spring values. Oxygen concentrations on the shelf above 25 m had become supersaturated to >10%, which continued into the basin (Fig. 6D). Size-fractionated productivity shows that growth in the low-biomass surface waters are dominated by particles less than 5 μm in diameter (Fig. 6E); particles over 5 μm contribute 50% or more to the production in the chlorophyll maximum.

4. Discussion

Spatial and temporal variation in the productivity of the Chukchi and Beaufort Seas can be attributed to environmental forcing, initially by irradiance, and then nutrient distribution. Spring productivity appears to be limited by ice cover over the study area, with higher rates in areas associated with leads and ice retreat. Spring phytoplankton communities were identified through analysis of chemotaxonomic photosynthetic pigments (Hill et al., 2005). On the shelf, diatoms and haptophytes, which are correlated with chlorophyll in particles over 5 μm and prasinophytes, which dominate the smaller size fractions, were present in mixed communities. Small-celled, dark-adapted prasinophytes dominated the basin communities. Upwards of 50% of production was observed in particles greater than

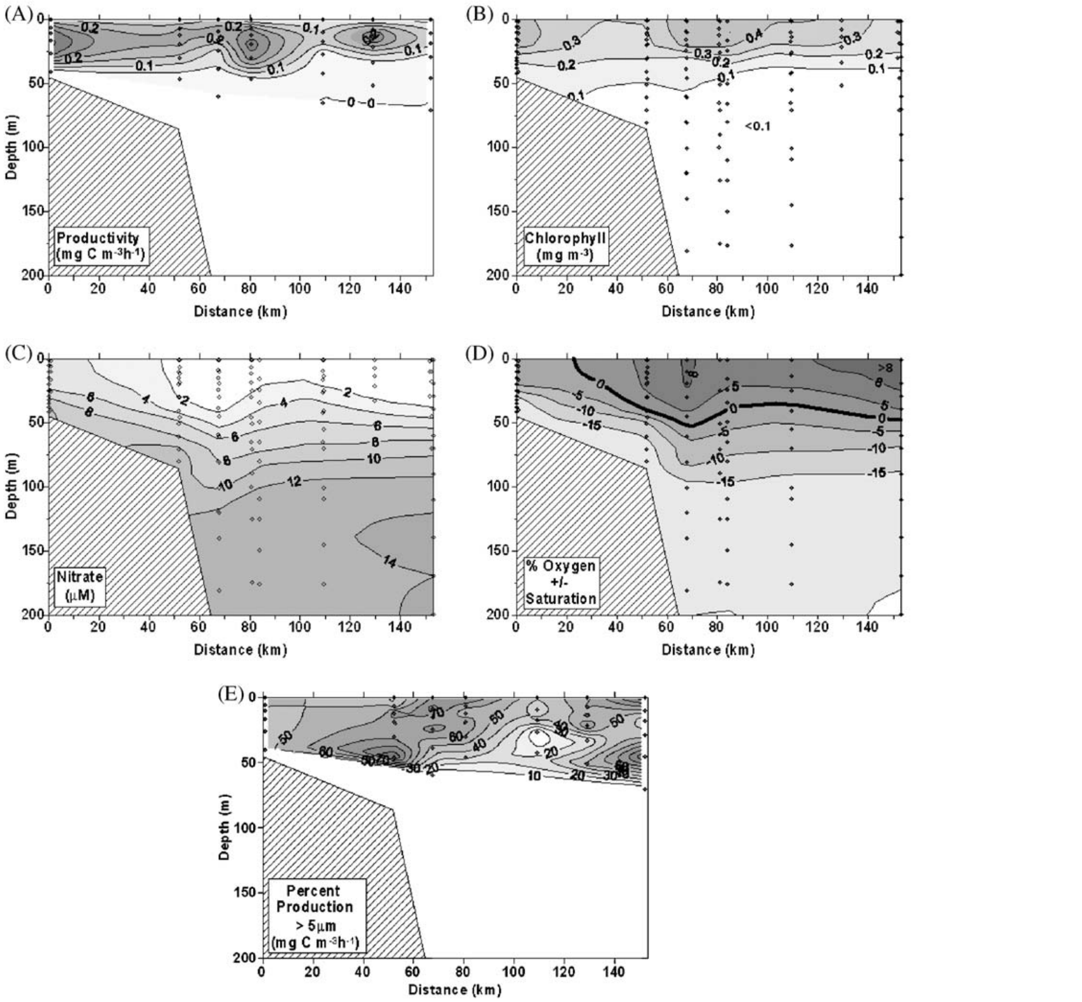

Fig. 5. (A) Primary productivity (based on 22–26 h incubations), (B) chlorophyll, (C) nitrate, (D) percent oxygen saturation (approximate depth of saturation is shown by a solid line) and (E) percent production in particles greater than 5 μm in the upper water column along the East Hanna Shoal transect from the continental shelf (< 5 μm) to the Canada Basin (> 2500 m) in the spring of 2002.

5 μm in size during the spring, linking this production to larger diatom and haptophyte species. These are the taxa that are best able to take advantage of high nutrient concentrations. They are rapidly growing (Jeffrey and Vesk, 1997) and are characteristic of the initial spring bloom in sub-polar and polar regions (Larsen et al., 2004). Oxygen concentrations over the shelf were observed to be at less than saturation, indicating that at this time there was no net oxygen production on the shelf, with autotrophic production being less than respiration. Oxygen concentrations increased over the basin, and this signal of supersaturation has also been observed in the central Arctic basin throughout the winter (English, 1961). These observations suggest that bacterial respiration is low over the winter due to reduction in labile organic matter and low temperature (Wiebe et al., 1992).

In the summer, nutrients appear to have been rapidly drawn down from the surface layer due to phytoplankton growth in the spring. Low to non-existent ice cover and a decrease in the attenuation of light in surface waters allowed phytoplankton to survive at greater depths and penetrate the nutricline resulting in a "deep" chlorophyll maximum at ~25 m. Daily productivity rates of 0.783 g C m^{-2} d^{-1} on the shelf were lower than those observed in the southern Chukchi Sea (Springer et al., 1993), but similar to highly productive coastal upwelling zones (Lalli and Parsons, 1995). Production was dominated by small

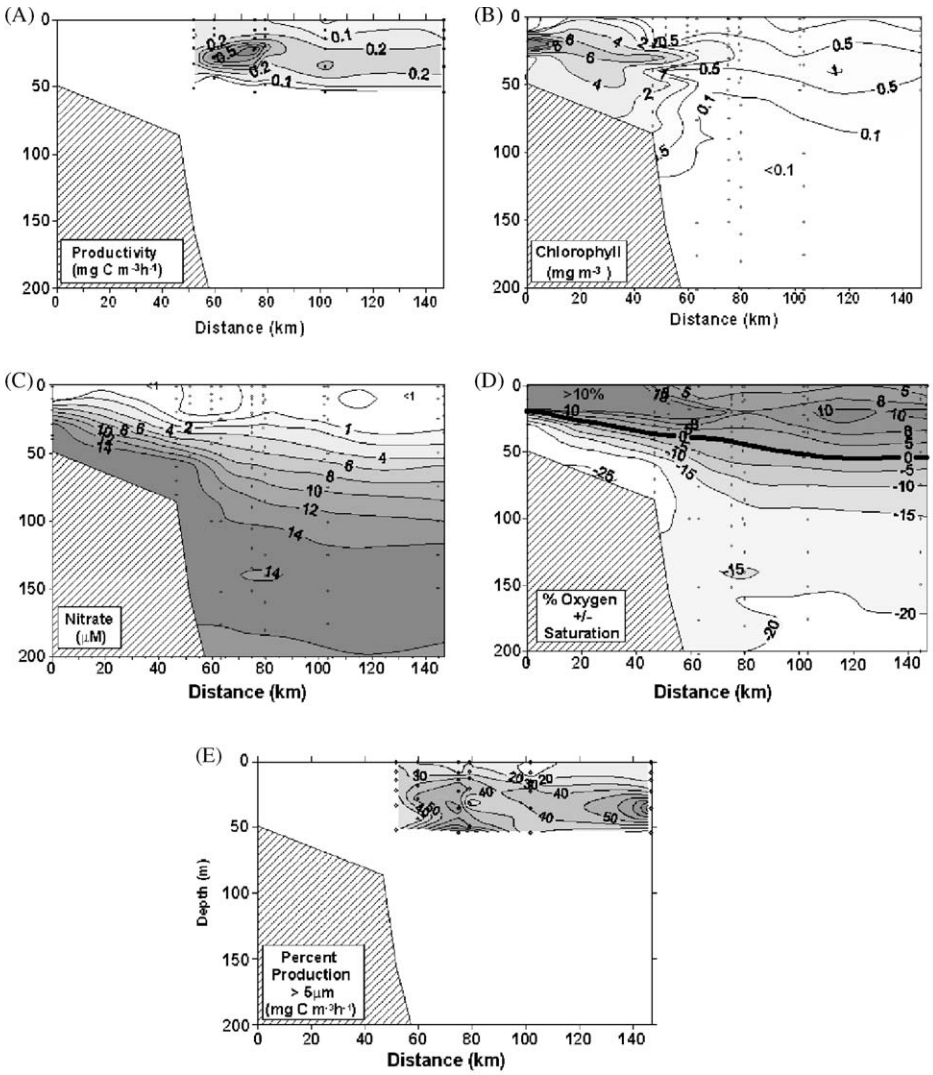

Fig. 6. (A) Primary productivity (based on 22–26 h incubations), (B) chlorophyll, (C) nitrate, (D) percent oxygen saturation (approximate depth of saturation is shown by a solid line), and (E) percent production in particles greater than 5 μm in the upper water column along the East Hanna Shoal transect from the continental shelf (< 50 m) to the Canada Basin (> 2500 m) in the summer of 2002.

particles at the surface and larger taxa in the subsurface chlorophyll maxima, consistent with post-bloom community structure (Larsen et al., 2004). Phytoplanktons have been identified as diatoms, haptophytes, and prasinophytes at the surface, with contributions of prasinophytes increasing over the basin (Hill et al., 2005). The subsurface maxima was dominated by diatoms. Larger phytoplankton and higher production rates at the subsurface chlorophyll maximum are characteristic of new production (Claustre, 1994), which is fueled by vertical mixing of nutrients from deeper water to the top of the nutricline. Lower production in smaller cells in the surface nutrient reduced layer is indicative of regenerated production. The increase in oxygen saturation between the spring and summer cruises indicates a net production of oxygen by the autotrophic community. This productivity observation and the reduced nutrients found in surface waters in the summer implies that significant photosynthesis took place between the spring and summer cruises indicative of the spring bloom. Satellite imagery from this time period predicts surface chlorophyll concentrations to be $> 10\,\mathrm{mg\,m^{-3}}$ (http://oceancolor.gsfc.nasa.gov/cgi/level3.pl), pointing towards missed spring bloom productivity that was considerably greater than the production rates observed in the nutricline during the summer.

Spatial variation in productivity during the summer is dictated by the chemical characteristics of the in-flow through the Bering Strait. There is an east–west gradient in water mass properties across the Chukchi shelf, with the highest nutrient concentrations found in the west as Anadyr influenced water flows from Bering Strait to Herald Valley (Codispoti et al., 2005). The higher instances of production observed in the Herald Valley location during the summer cruise are fueled by this northward-flowing Pacific water. Recent studies suggest the Barrow Canyon drains a significant part of the Chukchi shelf, including water from the Herald Valley current, which transports high-nutrient water and material from productive zones further south across the shelf (Woodgate et al., 2005). Episodic reversal of the northward-flowing Barrow Canyon current is observed due to local wind fields. This process allows Atlantic-derived water from below the pycnocline to penetrate into the canyon. Thus by these processes Barrow Canyon supports some of the highest PP rates of the Arctic. Its impact is evident in the benthic community, which was found to be high in biomass and diversity (Grebmeier, unpublished data; Dunton et al., 2005). This area also could be an important mechanism for the off-shelf export of material (Bates et al., 2005).

Annual production in the study area can be estimated using average production rates from the two cruises. The first cruise took place in May, and production although modest was observed, providing a starting date. The second cruise was completed at the end of August; however, in situ chlorophyll measurements from other years have observed chlorophyll biomass until the end of September (D. Stockwell, pers. com.). As the study area is still ice-free in September and >12 h of sunlight a day is still experienced above 70°N, a 150-d growing season can be assumed. Taking the mean ^{14}C photosynthetic rate during the spring as representative of the average daily rate for May and June, and the summer rates as representative of July, August, and September, the annual production is 70.5 g $C\,m^{-2}$ on the shelf and 19.8 g $C\,m^{-2}$ on the basin edge. This is likely an underestimation as evidence points to an unmeasured but pronounced phytoplankton bloom in the spring when ice first pulls back. Production by ice algae also was not taken into consideration, but has been estimated to contribute up to 10% to the total productivity (Gosselin et al., 1997). In the context of the remainder of the Arctic, this is higher than annual rates for the other shelf seas, with the exception of the Barents Sea (Sakshaug, 2004). If we calculate just the productivity of Barrow Canyon, based on the spring bloom rate of 8.2 g $C\,m^{-2}\,d^{-1}$ for June and summer rate of 2 g $C\,m^{-2}\,d^{-1}$ for July, August and September, then the annual production for this small region is ~430 g $C\,m^{-2}\,yr^{-1}$. This is comparable to the intense plume observed further south in the Gulf of Anadyr and Southern Chukchi Seas, which has an estimated annual production of up to 470 g $C\,m^{-2}\,yr^{-1}$, but which could be as high as 840 g $C\,m^{-2}\,yr^{-1}$ in the maximum production pools (Springer et al., 1993). Production outside of this plume has been estimated at 80 g $C\,m^{-2}\,yr^{-1}$, which is closer to that which was calculated for our whole study area, with the caveat that these are artificially low due to missing the spring bloom.

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