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Deep-Sea Research II 51 (2004) 1033–1051

DEEP-SEA RESEARCH
PART II

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Satellite and hydrographic observations of the Bering Sea 'Green Belt'

Stephen R. Okkonen[a,*], G.M. Schmidt[b], E.D. Cokelet[c], P.J. Stabeno[c]

[a]Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, Alaska 99775, USA
[b]SAIC, SeaWiFS Project, NASA, Goddard Space Flight Center, Greenbelt, MD 20771, USA
[c]NOAA, Pacific Marine Environmental Laboratory, Seattle, WA 98115, USA

Received 9 October 2002; accepted 20 August 2003
Available online 27 August 2004

Abstract

Green Belt is the aptly named region of high productivity occurring principally along and above the shelf-slope boundary in the Bering Sea. TOPEX altimeter measurements of sea-surface topography, SeaWiFS imagery of chlorophyll a concentration, and shipboard measurements of salinity and fluorescence are used to describe the surface structure of the Green Belt and its relationship to the Bering Slope Current eddy field during the 2000, 2001, and 2002 spring blooms. During spring 2000, high surface chlorophyll a concentrations ($>10\,\mathrm{mg\,m^{-3}}$) were observed within a ~200-km wide band adjacent to and seaward of the shelf break in the northwest Bering Sea. This high concentration chlorophyll band was associated with an anticyclonic eddy group that propagated along isobaths above the continental slope and entrained chlorophyll from the shelf-slope front. During spring 2001, anticyclonic eddies in the northwest Bering Sea had propagated off-slope prior to the onset of the spring bloom and were too far from the shelf-slope front to entrain frontal chlorophyll during the bloom. A second chlorophyll front associated with the leading edge of the off-slope eddies was observed. Between these two fronts was a region of relatively low chlorophyll a concentration (~$1\,\mathrm{mg\,m^{-3}}$). The eddy field during the 2002 spring bloom was observed to propagate northwestward adjacent to the shelf-break and entrain chlorophyll from the shelf-slope region in a manner similar to what was observed during the 2000 spring bloom. These observations suggest that eddies are important, if not the principal, agents that cause variability in the distribution of chlorophyll during the spring bloom in the central Bering Sea.

1. Introduction

Enhanced primary and secondary production often occurs where advective processes provide a steady supply of nutrients to the euphotic zone and coincidentally aggregate phytoplankton for efficient grazing by zooplankton. In a vertical plane transverse to the strong horizontal gradients of a frontal zone, these advective pathways describe a circulation pattern in which divergence and upwelling occur on the vertically mixed side of

*Corresponding author. Fax: +1-907-283-3234
E-mail address: okkonen@alaska.net (S.R. Okkonen).

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doi:10.1016/j.dsr2.2003.08.005

the front and convergence and downwelling occur on the stratified side of the front (e.g., James, 1978; Simpson et al., 1978: Garrett and Loder, 1981).

In the central Bering Sea, a shelf-slope front marking the boundary between relatively fresh shelf water and more saline basin water extends ~1000 km northwestward from Unimak Pass to near Cape Navarin (Kinder and Coachman, 1978; see also Fig. 1 for place name locations). This front is biologically significant because it coincides with the Bering Sea 'Green Belt', a region of tremendous primary production that supports an extensive variety of consumer species. Springer et al. (1996) provide annual production estimates (acknowledged likely to be underestimates) from a number of sources to show that primary and secondary production within the Green Belt exceeds production over the shelf and deep basin, and that fishes, seabirds, and marine mammals tend to congregate in the vicinity of the Green Belt in response to favorable feeding conditions. Hansell et al. (1989) argued that the shelf-slope front and its associated production are diverted northward onto the shelf near Cape Navarin to support production in the northern Bering Sea and southern Chukchi Sea.

While both of these review papers present generalized or schematic descriptions of the Green Belt, variability of this ecosystem is acknowledged.

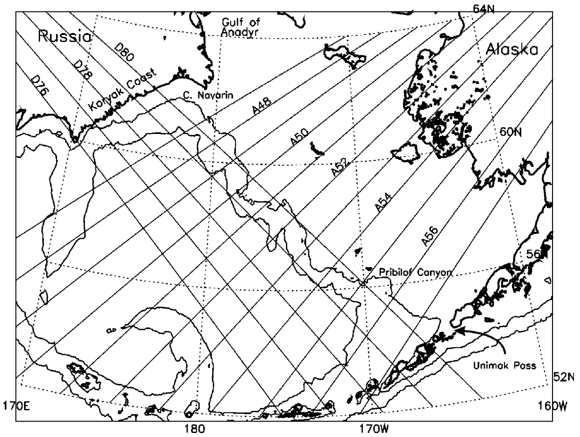

Fig. 1. Map of place names and selected TOPEX orbital ground tracks in the Bering Sea region. The 200 and 3000 m isobath contours are shown.

Variability in the structure and location of the frontal system defining the Green Belt region introduces variability to the advective pathways that support the production and distribution of planktonic species which, in turn, likely influence the distribution and/or foraging success of fishes, seabirds, and marine mammals that directly or indirectly exploit plankton.

An important advective component of this ecosystem is the Bering Slope Current (BSC); the eastern boundary current associated with the shelf-slope front (Kinder et al., 1975). The structure and flow of the BSC is modulated by a seasonally and interannually variable eddy field (Okkonen, 2001). It is the influence of this eddy field on the distribution of chlorophyll pigment in the Bering Sea Green Belt that is the subject of the research described in this paper.

2. Data

The TOPEX radar altimeter has acquired all-weather measurements of global sea-surface topography every 10 days since September 1992. For this study, nine and a half years (January 1993–July 2002; orbital repeat cycles 10–361) of TOPEX altimeter data (PO.DAAC Merged Geophysical Data Record, Generation B) were processed for the Bering Sea region. TOPEX orbital ground track locations in are shown in Fig. 1. Standard geophysical corrections (PO.DAAC, 1997) were applied to the data after which the geophysical data record mean sea surface was removed. Two-year (1993–1994) mean sea-surface heights were computed according to the method described by Leben et al., (1990) and then removed from the data. To reduce orbital height errors and other very long wavelength signals a quadratic was fit in a least-squares sense to each along-track profile of sea-surface heights and then removed. The resulting time–space matrix of sea-surface height anomalies (SSHA) is the working data set for this study.

The SeaWiFS ocean-color sensor has acquired daily visible band imagery of the earth since September 1997. Prospective, cloud-free SeaWiFS images of chlorophyll a (hereafter chlorophyll) concentrations in the surface waters of the central Bering Sea region were identified from the SeaWiFS HRPT web site (http://SeaWiFS.gfsc.nasa.gov) image archives for dates during the spring phytoplankton bloom (April–June, 1998–2002). While there were no dates for which the entire central Bering Sea was cloud free, there were a few dates (primarily in 2000 and 2001, and to a lesser extent 2002) for which large areas were cloud free. All SeaWiFs image data acquired for this research were processed using SeaDAS version 4.2 (McClain et al., 2000a, b; O'Reilly et al., 2000). Selected SeaWiFS images are presented in the following section to illustrate the gross characteristics of chlorophyll distribution and its variability in the central Bering Sea during the 2000, 2001, and 2002 spring blooms.

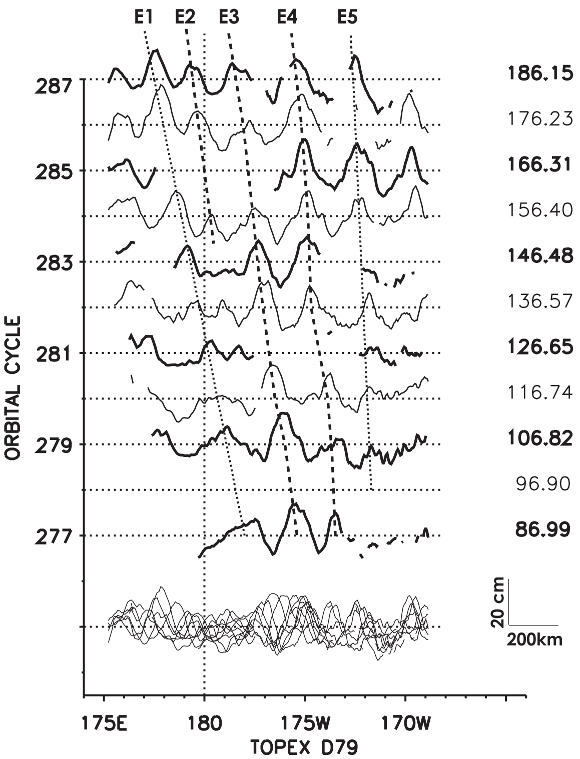

Fig. 2. SSHA profiles along orbital ground track D79, spring 2000. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The vertical dotted line indicates the longitude at which ground track A49 intersects D79. The oblique dotted lines illustrate the along-track (northwestward) components of propagation exhibited by anticyclonic eddies E1, E2, E3, E4, and E5. These eddies are also identified in subsequent SeaWiFS images. Oblique dotted lines for eddies E1 and E5 represent along-track phase speeds of 3.2 and 1.3 km d^{-1}, respectively. The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

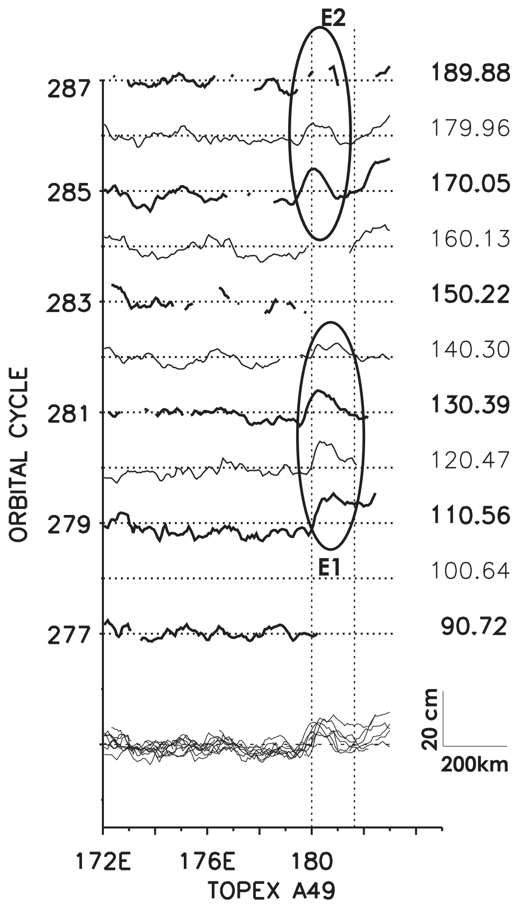

Fig. 3. SSHA profiles along orbital ground track A49, spring 2000. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The times during which eddies E1 and E2 intersect A49 are enclosed within the ellipses. The vertical dotted line at 180° indicates the longitude at which ground track A49 intersects D79. The vertical dotted line at 178.4°W indicates the longitude at which ground track A49 intersects the shelf break (200 m isobath). The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

3. Satellite observations of the Green Belt

3.1. Spring 2000

The orientation of the shelf break in the central Bering Sea is such that descending (northwest-to-southeast) TOPEX orbital ground tracks lie roughly parallel to the isobaths of the continental slope and ascending (southwest-to-northeast) orbital ground tracks lie roughly perpendicular to the isobaths (Fig. 1). Orbital ground track D79, in particular, is well located to permit monitoring of the Bering Slope Current (BSC) eddy field.

A 3-month sequence of SSHA profiles along D79 shows the along-isobath evolution of the BSC eddy field during spring 2000 (Fig. 2). Positive SSHA with length scales exceeding a few tens of kilometers are interpreted to be the topographic signatures of anticyclonic meanders and eddies, hereafter eddies, whereas negative SSHA with length scales exceeding a few tens of kilometers are interpreted to be the topographic signatures of cyclonic eddies. Eddies exhibit northwestward components of propagation ranging between 1.3 and 3.2 km d^{-1}. Representative SSHA amplitudes and wavelengths are ~10 cm and ~200 km, respectively. The corresponding wave periods range from ~60 to ~150 days.

A companion 3-month sequence of SSHA profiles along orbital ground track A49 shows a cross-isobath history of the eddy field in the northwestern Bering Sea during spring 2000

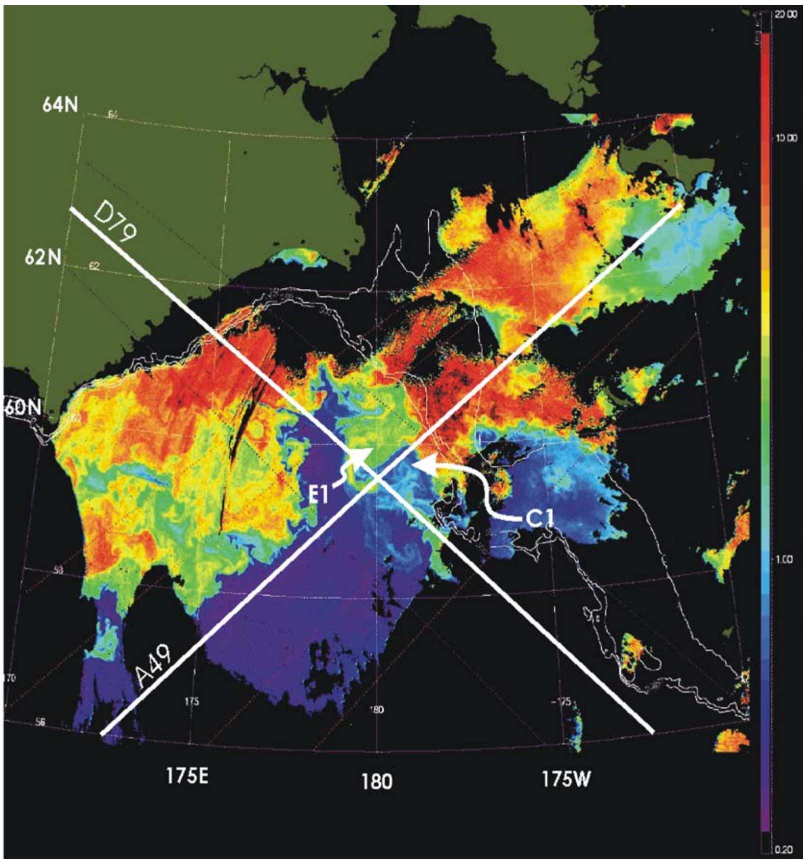

Fig. 4. SeaWiFs false-color image of chlorophyll a concentration for 18 May 2000. The chlorophyll concentration scale ranges from 0.2 to 20 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. Ground tracks D79 andA49 are highlighted. The 200 and 3000 m isobaths are contoured.

(Fig. 3). Comparison of these SSHA profiles with the profiles along D79 (cf. Fig. 2) indicates two separate anticyclonic eddies propagating along D79 cross A49 between 180°W and 179°W. The available SSHA profiles show that the first of these eddies (E1) crosses A49 during cycles 279–282 (days ~110–140) and that the second eddy (E2) crosses A49 during cycles 285–287 (days ~170–189). The eddy trajectories are largely confined to the vicinity of the continental margin and exhibit very little cross-isobath propagation. Although not shown, this situation is generally true for eddy activity along other ascending ground tracks (except for A51) in the central Bering Sea during spring 2000.

A false-color image of the chlorophyll concentration in the central Bering Sea on 18 May 2000 (day139) is shown in Fig. 4. Comparison of the true-color image for this date (not shown) with the false-color image indicates that the black areas next to the Koryak coast and within the Gulf of Anadyr are ice-covered, whereas the black areas in the southeastern Bering Sea are cloud-covered. Black is used in SeaWiFS imagery to denote areas in which valid chlorophyll concentrations cannot be determined due to conditions such as ice, high sediment concentrations, shallow water, or excluded atmospheric corrections. Chlorophyll concentrations exceeding 10 mg m^{-3} are evident near the Koryak coast and in the vicinity of the Gulf of Anadyr. Due to the presence of sea ice along the coast we infer that the high chlorophyll concentrations are likely associated with near-surface stratification derived from melting sea ice.

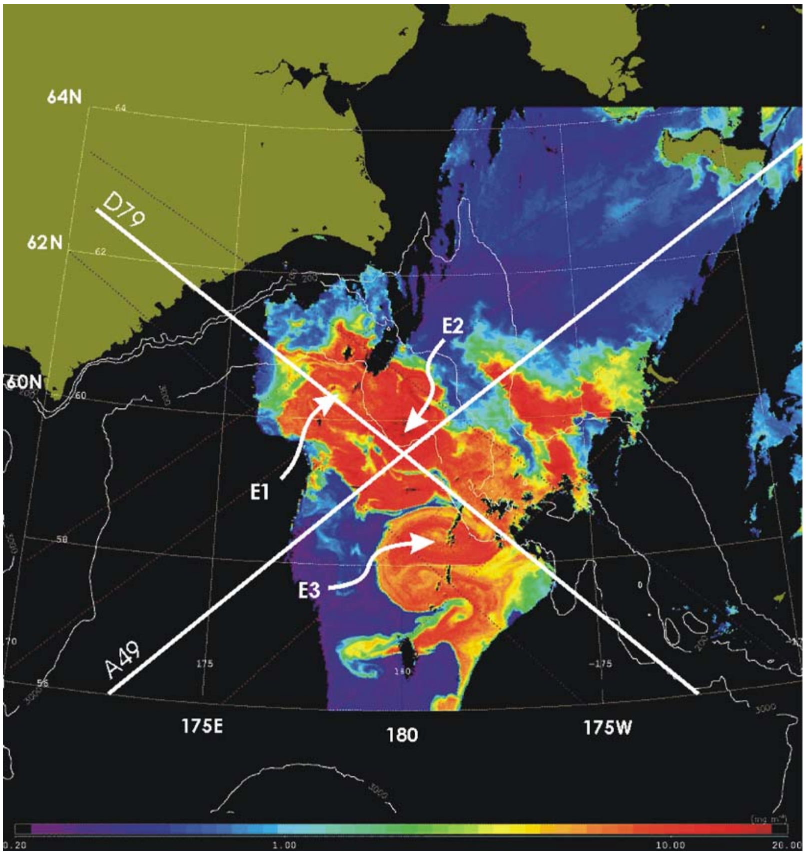

Fig. 5. SeaWiFs false-color image of chlorophyll a concentration for 14 June 2000. The chlorophyll concentration scale ranges from 0.2 to 20 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. Ground tracks D79 andA49 are highlighted. The 200 and 3000 m isobaths are contoured.

An eddy (E1) centered at ~60°N, 180°E is entraining chlorophyll from the region of high chlorophyll over the shelf. Inspection of the SSHA profiles bracketing day 139 in Figs. 2 and 3 show that the SSHA associated with this eddy is positive thereby indicating that the sense of rotation is locally anticyclonic. The trace of chlorophyll pigments in the low chlorophyll region centered at ~59.5°N, 179°W suggests cyclonic flow (C1). Together these two counter-rotating flows define a dipole eddy. The region of low chlorophyll on the western flank of the anticyclonic eddy suggests an intrusion of more saline basin water across the high-chlorophyll region of the inferred melt water plume. The sliver of coverage near 56°N, 170°W indicates moderate-to-high chlorophyll concentrations (~5–20 mg m^{-3}) over this portion of the outer shelf and continental slope.

The SeaWiFS image acquired on 14 June 2000 (day166) shows that the chlorophyll distribution has changed markedly since mid-May (Fig. 5). Chlorophyll concentrations near the Koryak coast and in the Gulf of Anadyr are now low whereas the highest concentrations (~5–15 mg m^{-3}) are generally found within a ~200-km wide band of eddies on the seaward side of the shelf break. Three prominent anticyclonic eddies centered at ~60.5°N, 178°E (E1), 59.7°N, 180°E (E2), and 58.5°N, 179°W (E3) are entraining chlorophyll from the shelf-slope front. The northernmost of these eddies (E1) has propagated ~100 km west northwestward from its earlier-observed location (60°N, 180°E) in the 18 May 2000 image. Eddy E2 is difficult to distinguish from the shelf-slope front, but its presence can be inferred from the altimeter record (cf. Fig. 2). The northwestward, along-slope propagation of these three eddies also is confirmed in the altimeter record (cf. Fig. 2).

The 27 June 2000 SeaWiFS image (day179) shows chlorophyll concentrations over a large portion of the central and eastern Bering Sea (Fig. 6). Comparison of this image with the

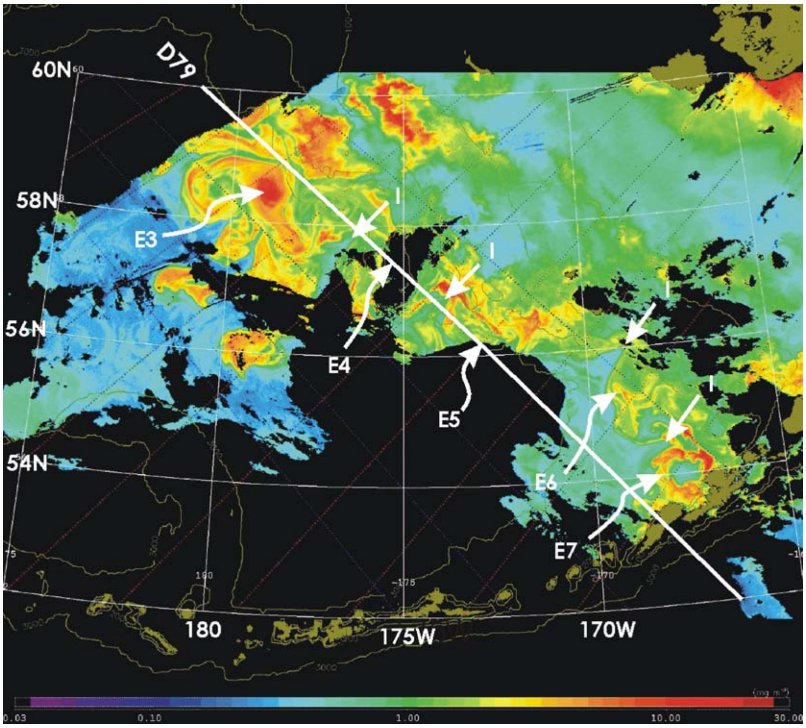

Fig. 6. SeaWiFs false-color image of chlorophyll a concentration for 27 June 2000. The chlorophyll concentration scale ranges from 0.03 to 30 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. Ground track D79 is highlighted. The 200 and 3000 m isobaths are contoured. Arrows annotated with the letter I indicate on-shelf intrusions of low-chlorophyll, basin water.

previous image indicates that surface chlorophyll concentrations associated with the shelf-slope front and eddy field near 180° are generally lower. The lower chlorophyll concentrations might reasonably be attributed to thermal stratification, which increases throughout the spring and summer in the Bering Sea basin (Cokelet and Stabeno, 1997). A consequence of increasing thermal stratification is that chlorophyll maxima are relegated to the vicinity of the seasonal pycnocline (Mizobata et al., 2002). In the southeastern Bering Sea anticyclonic eddies near 57.3°N, 175.3°W (E4, largely obscured by clouds), 56.3°N, 172.5°W (E5, somewhat obscured by clouds), 55.5°N, 169°W (E6), and 54°N, 167.5°W (E7) appear to be entraining chlorophyll from the shelf-slope front. On-shelf intrusions of lower chlorophyll basin water, observed on the leading (northwestern)

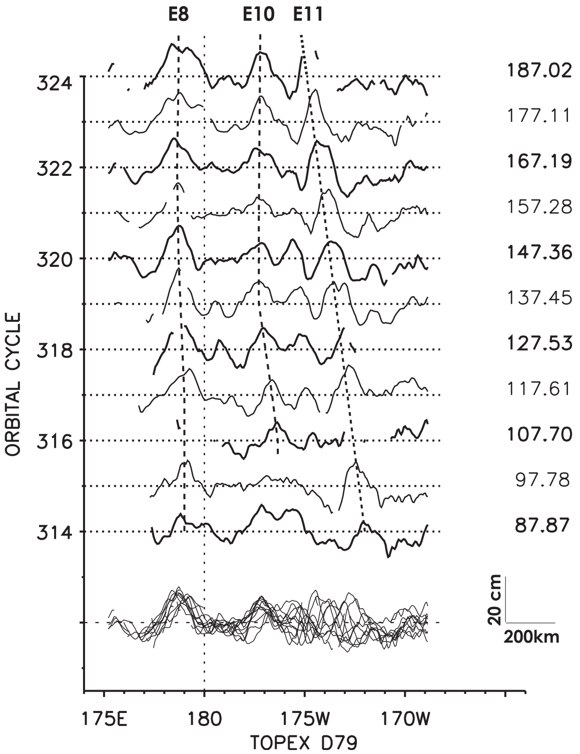

Fig. 7. SSHA profiles along orbital ground track D79, spring 2001. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The vertical dotted line indicates the longitude at which ground track A49 intersects D79. The oblique dotted lines illustrate the along-track (northwestward) components of propagation exhibited by anticyclonic eddies E8, E10, and E11. These eddies are also identified in subsequent SeaWiFS images. The oblique dotted line for eddy E11 represents an along-track phase speed of 2.4 km d^{-1}. The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

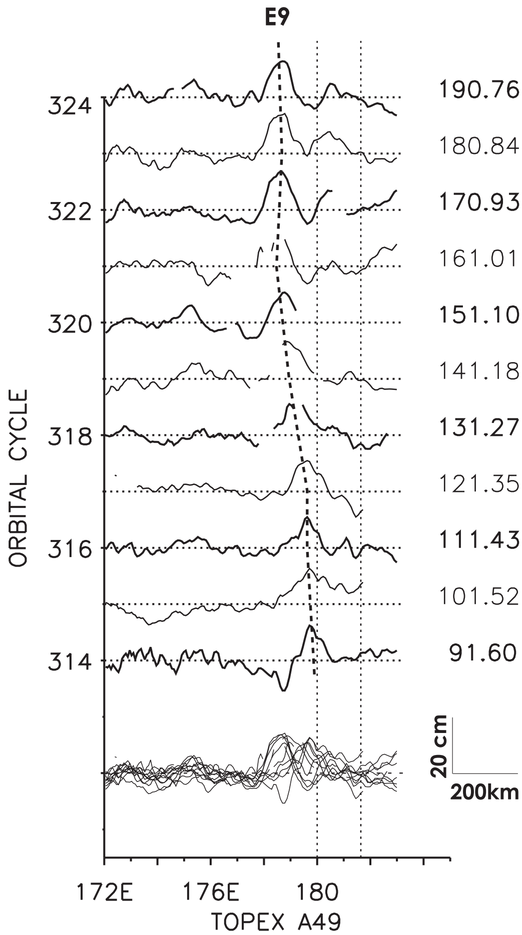

Fig. 8. SSHA profiles along orbital ground track A49, spring 2001. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The vertical dotted line at 180° indicates the longitude at which ground track A49 intersects D79. The vertical dotted line at 178.4°W indicates the longitude at which ground track A49 intersects the 200 m isobath (nominal shelf break). The oblique dotted line illustrates the along-track (southwestward) component of propagation exhibited by anticyclonic eddy E9. The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

flanks of these anticyclonic eddies, are indicated with arrows annotated with the letter I in the figure.

3.2. Spring 2001

Fig. 7 shows the 3-month sequence of SSHA profiles along D79 during spring 2001. Comparison of the eddy activity along this ground track with that of the previous spring (cf. Fig. 2) shows that, while representative eddy amplitudes and wavelengths are similar for the 2 years, there is little along-slope propagation west of ~177°W in 2001. The eddies observed between 172°W and 176°W exhibit northwestward components of propagation at ~2.4 km d^{-1}.

Fig. 8 shows 3-month sequence of SSHA profiles along A49 during spring 2001. These profiles are markedly different from the SSHA profiles observed along this ground track during the previous year (cf. Fig. 3). The spring 2001 profiles show a large anticyclonic eddy (E9) whose nearshore flank lies ~70 km from the shelf break at the beginning of April (day 91). By the end of May (day 151) eddy E9 has propagated well off-slope.

An image from 29 April 2001 (day119) shows a chlorophyll plume along the Koryak coast (Fig. 9). The true-color image for this date (not shown) shows sea ice in the Gulf of Anadyr and south of Cape Navarin, suggesting that the high chlorophyll regime is associated with a melt water plume

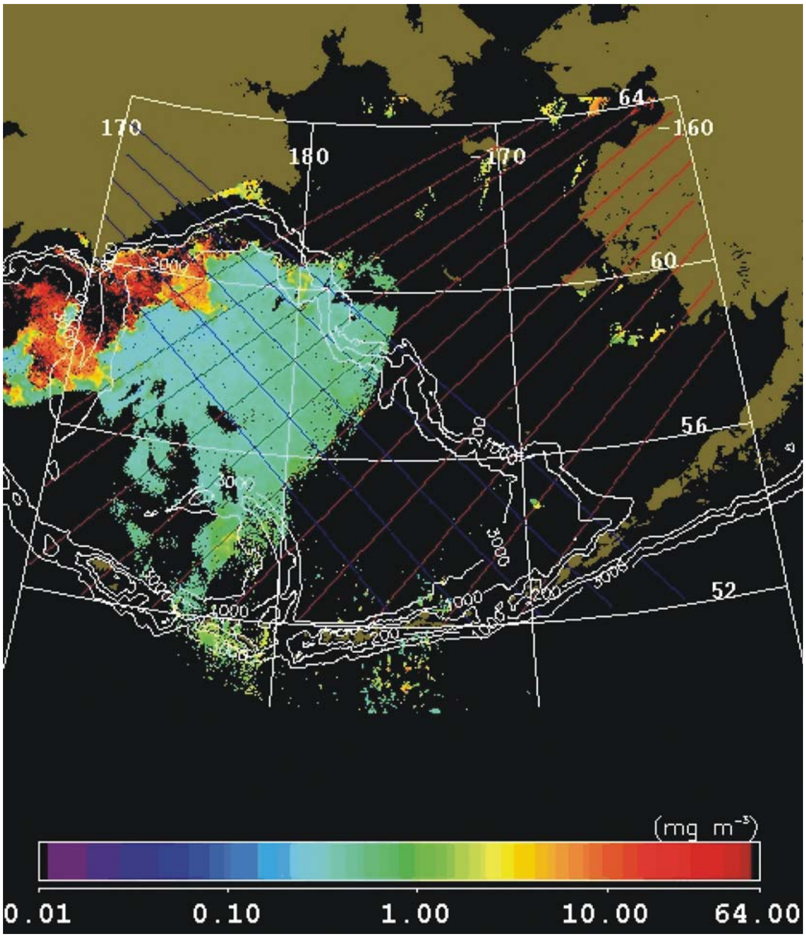

Fig. 9. SeaWiFs false-color image of chlorophyll a concentration for 29 April 2001. The chlorophyll concentration scale ranges from to 64 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. The 200 and 3000 m isobaths are contoured.

originating at the ice edge. Chlorophyll concentrations over the continental slope between ~176°W and 180° and within the remainder of the Aleutian Basin are low. The low chlorophyll concentrations over the continental slope in the central Bering Sea suggest that there is not yet sufficient stratification in the shelf-slope front to support enhanced productivity in the surface layer.

The 7 June 2001 (day 158) chlorophyll image (Fig. 10) shows that sea ice is gone from the northwestern Bering Sea and that the early bloom along the Koryak coast has dissipated. The prominent, 200-km wide, high-concentration chlorophyll band of the previous year is also absent. Instead, high chlorophyll concentrations (5–20 mg m^{-3}) delineate a front on the shoal side of the shelf break between 173°W and 179°W as well as an off-shelf front extending from ~57°N, 178°E to 61°N, 177.5°E. The northern half of this off-shelf front lies on western flanks of two anticyclonic eddies, E8 and E9 (cf. Figs. 7 and 8). Two anticyclonic eddies, centered near 58°N, 177.5°W (E10) and 56.7°N, 174°W (E11), have somewhat higher chlorophyll concentrations than their immediate surroundings. Of these two eddies, the more easterly eddy lies closer to the shelf and is seen to be entraining chlorophyll along its trailing flank from what might be the shelf-slope front. SSHA along D79 (cf. Fig. 7) show that this eddy (E11) has a northwestward component of propagation (~2.4 km d^{-1}) whereas the more westerly eddy (E10) exhibits little along-slope propagation during the latter half of the record. A broad, zonally oriented band of chlorophyll pigment

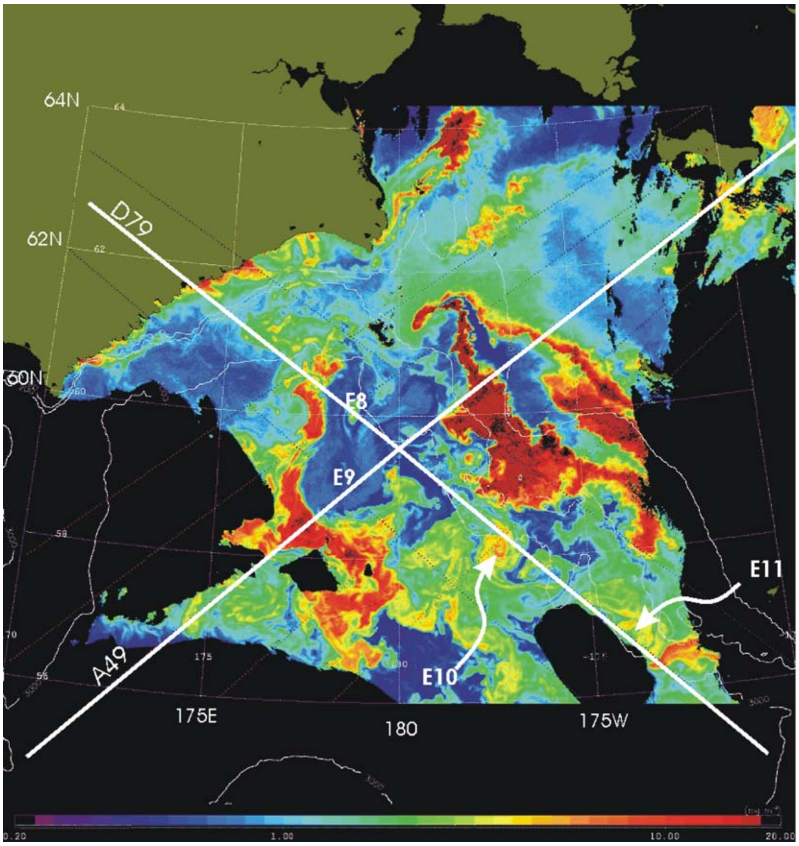

Fig. 10. SeaWiFs false-color image of chlorophyll a concentration for 7 June 2001. The chlorophyll concentration scale ranges from 0.2 to 20 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. Ground tracks D79 andA49 are highlighted. The 200 and 3000 m isobaths are contoured.

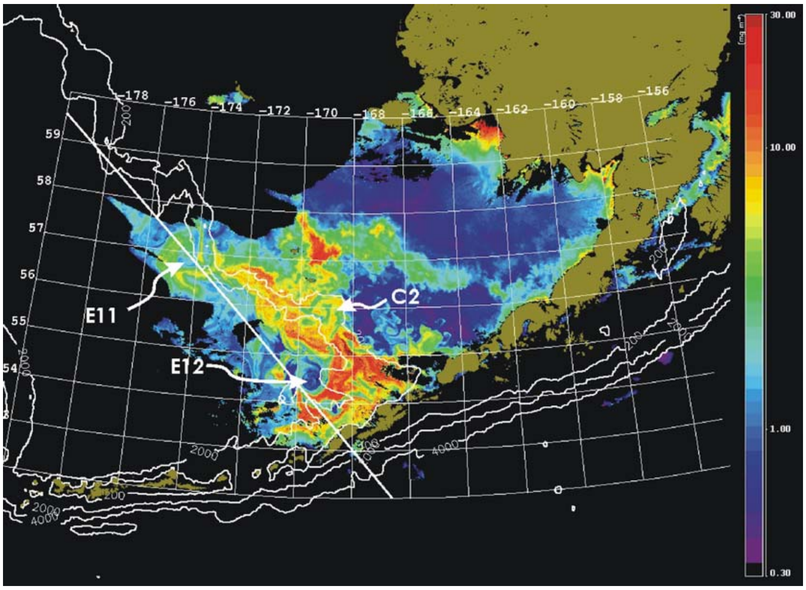

Fig. 11. SeaWiFs false-color image of chlorophyll a concentration for 18 June 2001. The chlorophyll concentration scale ranges from 0.3 to 30 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. Ground track D79 is highlighted. The 200 and 3000 m isobaths are contoured.

centered on 57.5°N and extending westward from the continental shelf may indicate separation of the BSC from the continental margin.

The SeaWiFS image acquired on 18 June 2001 (day 169) shows high surface chlorophyll concentrations over the continental slope in the southeastern Bering Sea (Fig. 11). A number of small eddies, revealed by their low chlorophyll cores, are seen to be embedded within the shelf-slope front. Their presence increases the local cross-slope width of the Green Belt. A cyclonic eddy (C2) occupying Pribilof Canyon is entraining chlorophyll from the front. Anticyclonic eddies centered near 54.5°N, 169.5°W (E12) and 56.7°N, 175°W (E11, see also Fig. 10) are drawing chlorophyll from the front around their peripheries. Chlorophyll concentrations along D79 between these two anticyclonic eddies are relatively low.

3.3. Spring 2002

The 3-month sequence of SSHA along D79 during spring 2002 (Fig. 12) shows a well-developed shelf-break eddy field that exhibits a slow northwestward component of propagation (<1 km d^{-1}). Representative SSHA amplitudes and wavelengths are ~10 cm and ~200 km, respectively. This eddy field is qualitatively similar to the spring 2000 eddy field (cf. Fig. 2) except that the along-slope propagation speeds are slower than were observed during spring 2000.

SSHA along ground track A49 (Fig. 13) show that the ~100-km diameter eddy (E14) just seaward of the shelf-break exhibits a very weak cross-slope component of propagation from early April through early June (days 93–152). Thereafter, the eddy exhibits a cross-slope component of propagation of ~1.6 km d^{-1}. In the southeastern Bering Sea, SSHA along ground track A54 (Fig. 14) shows a prominent (~20-cm height, ~100-km diameter) anticyclonic eddy (E15) remains just seaward of the shelf-break from late March (day 88) to late May (day 147) as it crosses the ground track.

Collectively, Figs. 12–14 indicate that eddies E13, E14, and E15 remain close to the shelf-break for much of the spring. SSHA profiles from other ascending ground tracks (not shown) indicate that other shelf break eddies also remain close to the shelf for much of the spring. One exception is an

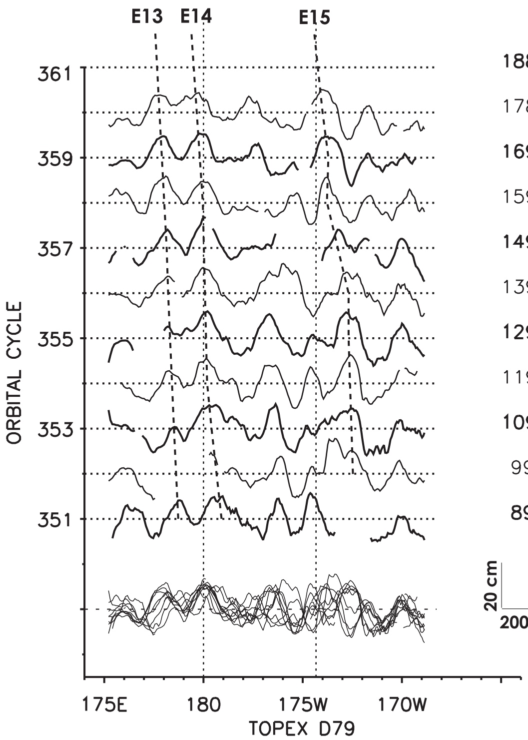

Fig. 12. SSHA profiles along orbital ground track D79, spring 2002. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The vertical dotted lines indicate the longitudes at which ground tracks A49 (180°) and A54 (172.9°W) intersect D79. The oblique dotted lines illustrate the along-track (northwestward) components of propagation exhibited by anticyclonic eddies E13, E14, and E15. These eddies are also identified in subsequent SeaWiFS images. The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

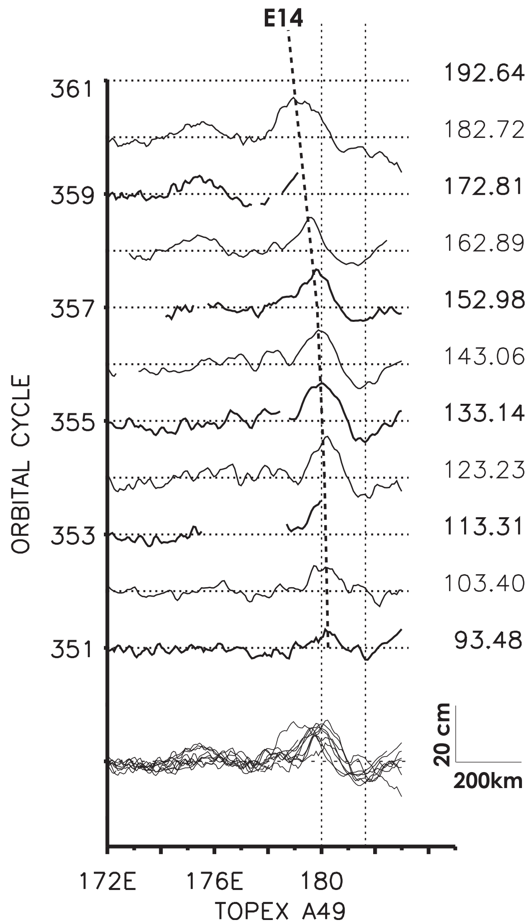

Fig. 13. SSHA profiles along orbital ground track A49, spring 2002. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The vertical dotted line at 180° indicates the longitude at which ground track A49 intersects D79. The vertical dotted line at 178.4°W indicates the longitude at which ground track A49 intersects the shelf break (200 m isobath). The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

eddy that propagates off-slope near ground track A52. Based upon observations of the year 2000 spring bloom we might expect that these shelf-break eddies will entrain exisiting chlorophyll from the outer shelf and upper slope.

A SeaWiFS image from 15 May 2002 (day 135) shows the chlorophyll distribution over much of the central Bering Sea (Fig. 15). A striking feature of this image is that, while there are high chlorophyll areas at the shelf-break near the northwest and southeast edges of the cloud-free area, there is no shelf-slope chlorophyll front between ~173°W and 177°W. Eddy E15, centered near 56°N, 173°W, appears to be entraining shelf/slope chlorophyll about its periphery. The chlorophyll tongue at 56.3°N and extending westward from eddy E15 is associated with the southern flank of an anticyclonic eddy that intersects ground track A53 near ~175°W.

A SeaWiFS image acquired eight days later on 23 May 2002 (day 143) shows the chlorophyll

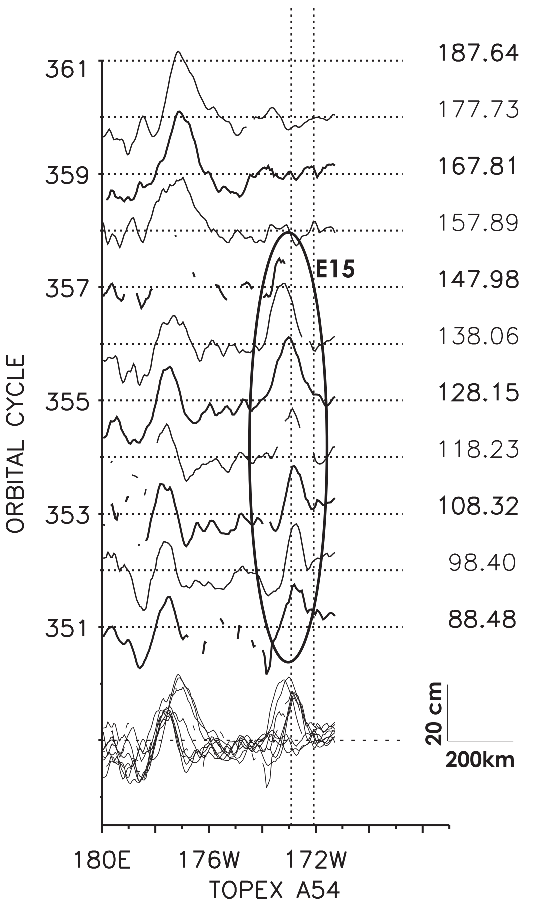

Fig. 14. SSHA profiles along orbital ground track A54, spring 2002. Sequential profiles are offset from one another by 20 cm. Height and length scales are shown near the lower right corner of the figure. All profiles are shown without temporal offsets at the bottom of the plot. The times during which eddy E15 intersects A54 are enclosed within the ellipse. The vertical dotted line at 172.9°W indicates the longitude at which ground track A54 intersects D79. The vertical dotted line at 172.05°W indicates the longitude at which ground track A54 intersects the shelf break (200 m isobath). The decimal day of year corresponding to each orbital cycle is given to the right of each profile.

distribution over much of the central and northwestern Bering Sea (Fig. 16). Eddies centered near 60.3°N, 178.5°E (E13), and 59.6°N, 180° (E14) have relatively high chlorophyll (~5 mg m^{-3}) cores, the source of which appears to be chlorophyll entrained from the upper slope and/or outer shelf. Eddy E15 has moved slightly northwestward to near 56.2°N, 173.8°W, while the chlorophyll concentration on its northern flank appears to have increased since day 135. Comparisons with Figs. 12–14 indicate that eddies E13, E14, and E15 are anticyclonic. SSHA from ground track A48 (not shown) indicate that eddy C3 is cyclonic.

4. Hydrography

Shipboard measurements in the Bering Sea Green Belt confirm that eddies deflect shelf water into the basin. Hydrography was acquired from the Green Belt region during the 2001 spring bloom between 31 May and 8 June (days 151–159) in the southeast Bering Sea during cruise RB-01-03 Leg 3 on NOAA Ship *Ronald H. Brown*. Sixty-nine vertical casts of temperature and salinity were made with a Sea-Bird SBE 911plus CTD (conductivity/temperature/depth) instrument with dual temperature and conductivity sensors on a grid with a station spacing of eight nautical miles in the vicinity of Pribilof Canyon (Fig. 17). Geostrophic currents were computed referred to 1500 dbar (decibar $= 10^4$ Pa) or the ocean bottom, if shallower. Four satellite-tracked drifting buoys drogued at 40 m also were deployed. Surface salinity isolines (Fig. 17) generally show increasing salinity off-shelf. The shelf-slope front characterized by a strong horizontal salinity gradient crosses the eastern wall of Pribilof Canyon near 55.9°N, 168.7°W and is deflected seaward around an anticyclonic eddy located over the canyon mouth. The eddy center (perhaps with dual cores though not well resolved) has a salinity characteristic of the outer shelf indicating entrainment of lower salinity water. SSHA data (not presented) from TOPEX orbital ground track D80 shows the eddy corresponds to sea-surface topographic high. Geostrophic velocity vectors give anticyclonic flow parallel to the 32.6 psu eddy salinity contour. Near the shelf-edge the clockwise eddy is not strong enough to reverse the northwestward Bering Slope Current, but it does slow it down as shown by the drifting buoy (magenta, Fig. 17), which slowly follows the continental slope remaining within the study area for 12 days. A drifter (red, Fig. 17) deployed in the eddy makes a clockwise loop before moving downstream. The anticyclonic eddy

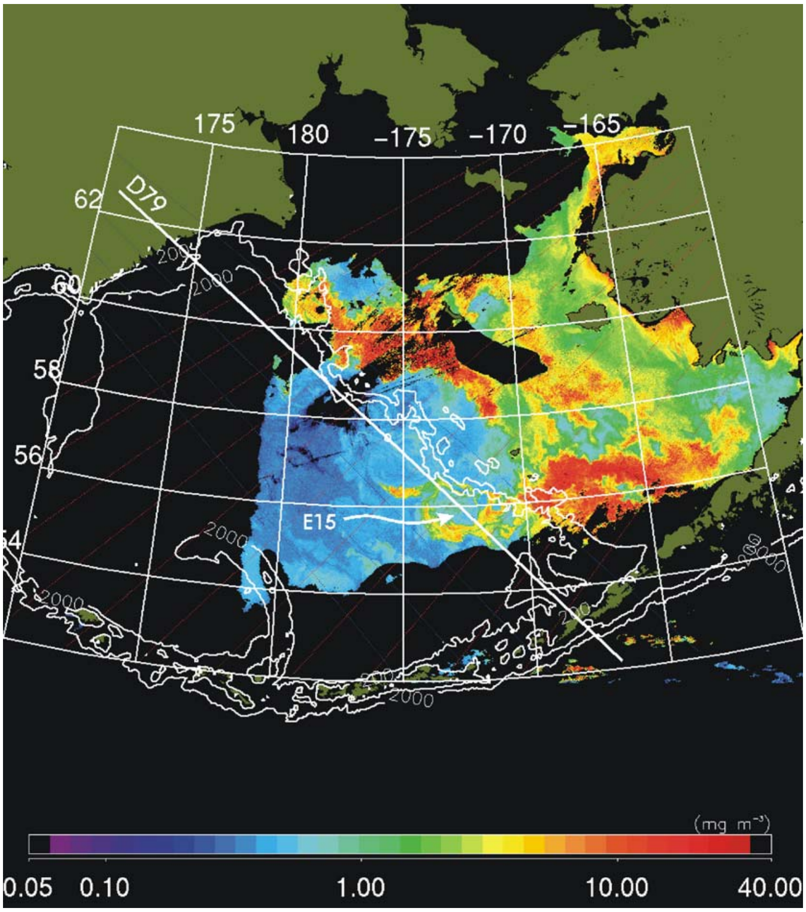

Fig. 15. SeaWiFs false-color image of chlorophyll a concentration for 15 May 2002. The chlorophyll concentration scale ranges from 0.05 to 40 $mg\,m^{-3}$. Topex orbital ground track locations are overlaid on the image. Ground tracks A49, A54, and D79 are highlighted. The 200 and 3000 m isobaths are contoured.

abuts a counter-rotating eddy to seaward with high surface salinity (32.9–33.0 psu) and cyclonic flow as shown by the geostrophic vectors. It deflects a drifter (black, Fig. 17) first northward and then westward where it joins the other and moves off rapidly, pinched between the eddy pair.

The *Ronald H. Brown* carried a flow-through Turner fluorometer plumbed to the ship's sea chest a few meters below the surface and sampled every 30 s. Although not calibrated, it gives an estimate of relative chlorophyll concentration. An along-track plot of relative fluorescence (Fig. 18) generally shows an increase off-shelf. Low fluorescence in the core of the anticyclonic eddy and high fluorescence around its perimeter are consistent with the entrainment of outer-shelf water into the basin.

5. Discussion

This paper presents observations of chlorophyll concentration although a more useful ecological measure is primary production. If chlorophyll concentration is a proxy for primary production, then chlorophyll that is advected offshelf/offslope by eddies represents a production increase for the basin and a production loss for the shelf/slope. However, secondary (vertical) circulation associated with eddies can introduce new nutrients to

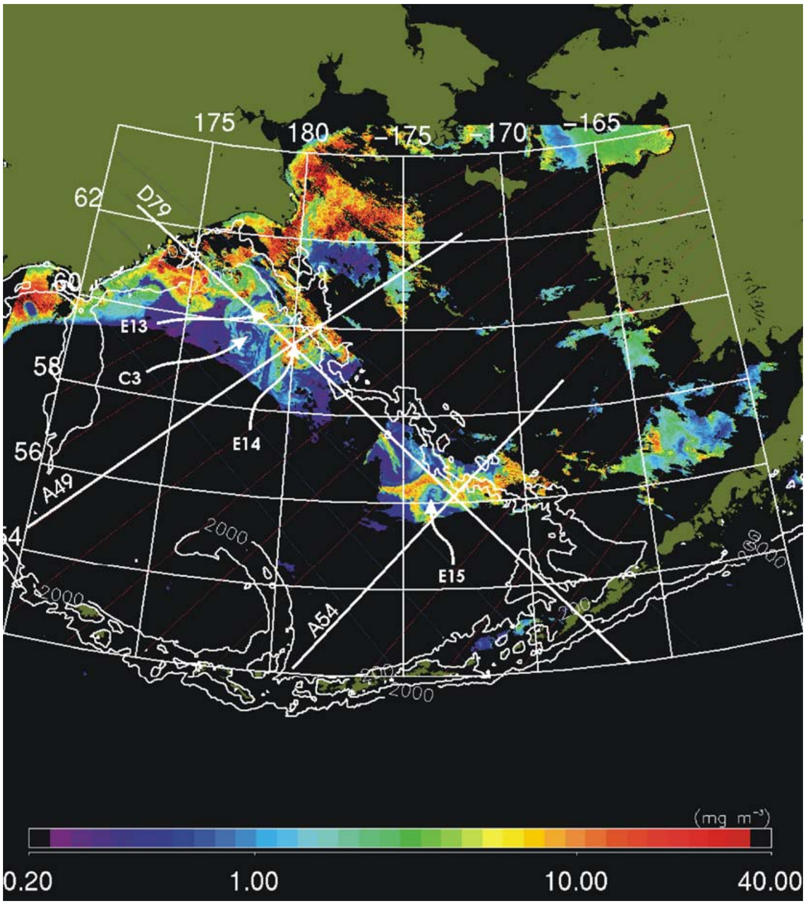

Fig. 16. SeaWiFs false-color image of chlorophyll a concentration for 23 May 2002. The chlorophyll concentration scale ranges from 0.20 to 40 mg m^{-3}. Topex orbital ground track locations are overlaid on the image. Ground tracks A49, A54, and D79 are highlighted. The 200 and 3000 m isobaths are contoured.

the euphotic zone and stimulate new production. Whether this new production occurs over the shelf/slope or over the basin, a local productivity gain results. That said, to estimate primary production reliably, based in part, on satellite observations of ocean color is not trivial. A representative method, reviewed by Platt and Sathyendranath (1988), depends primarily on chlorophyll concentration and available light. Secondary factors include nutrients, temperature, and phytoplankton species composition. Of these factors only surface chlorophyll and (sea-surface) temperature can be directly measured by satellites. Furthermore, vertical variations in each of these factors cannot be directly measured by satellites and introduce additional complexities to the problem of estimating primary production. While these factors might be roughly described or modeled over basin scales (O 1000 km), the observations presented in the preceding sections demonstrate that the greatest variability in the concentration and distribution of chlorophyll in the Bering Sea basin occurs not at the basin scale, but at scales associated with the mesoscale eddy field. It can be reasonably inferred that the other factors also exhibit the greatest variability at the mesoscale. Because clouds typically obscure much of the Bering Sea for periods comparable to eddy time scales (tens of days) the acquisition of sufficient ocean-color imagery to resolve

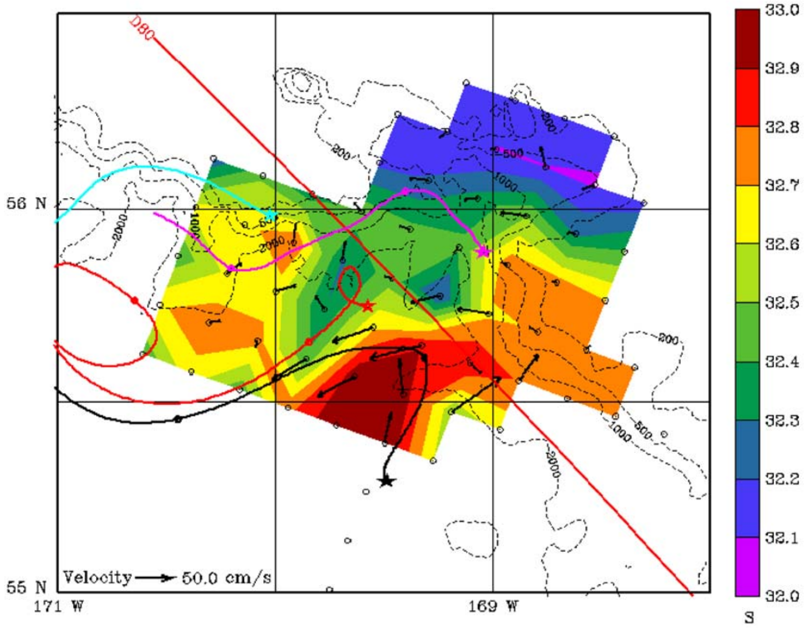

Fig. 17. Surface salinity in the southeast Bering Sea over Pribilof Canyon, 31 May–8 June 2001, as measured from 69 CTD casts on an 8-n.mi. grid. The salinity contour interval is 0.1 psu. Isobaths are shown in black at 200, 500, 1000 and 2000 m. Vectors represent the geostrophic velocity referred to the shallower of 1500 dbar or the bottom. A scaling vector in cm/s is drawn at lower left. The 24-h-smoothed trajectories of four satellite-tracked drifting buoys are drawn as magenta, red, black and cyan curves. The trajectories are marked with stars at their starting points and closed circles every subsequent 5 days. Also shown is Topex orbital ground track D80.

variability of the chlorophyll concentration and, therefore, primary production at the mesoscale (O 100 km; O 10–100 days) in the Bering Sea Green Belt is not likely. If spatial or temporal averaging of surface chlorophyll concentrations is employed to compensate for extensive cloud cover, the results will be both biased and aliased to longer length scales and periods, the effects of which are to obscure the mesoscale variability. For these reasons this research has focused on the distribution of chlorophyll.

TOPEX altimeter measurements of SSHA and SeaWiFS imagery of chlorophyll concentrations have been used to illustrate relationships between the eddy fields and distributions of chlorophyll in the central Bering Sea during the 2000, 2001, 2002 spring blooms. Although there are few clear-sky SeaWiFS chlorophyll images of spring bloom conditions, consideration of the available imagery within the context of the SSHA record and the surface hydrography lead us to make a few generalizations with respect to the surface structure of the Bering Sea Green Belt.

The nominal location and width of the Green Belt correspond to the location and width of the shelf-slope front. An anticyclonic eddy that lies on the basin side of the shelf break and is adjacent to the shelf will entrain surface water from the outer shelf/upper slope. If this phenomenon occurs during the spring bloom when there are high chlorophyll concentrations associated with the shelf-slope front, the eddy will entrain chlorophyll and effect a locally wider Green Belt. This phenomenon was evident during the 2000 and

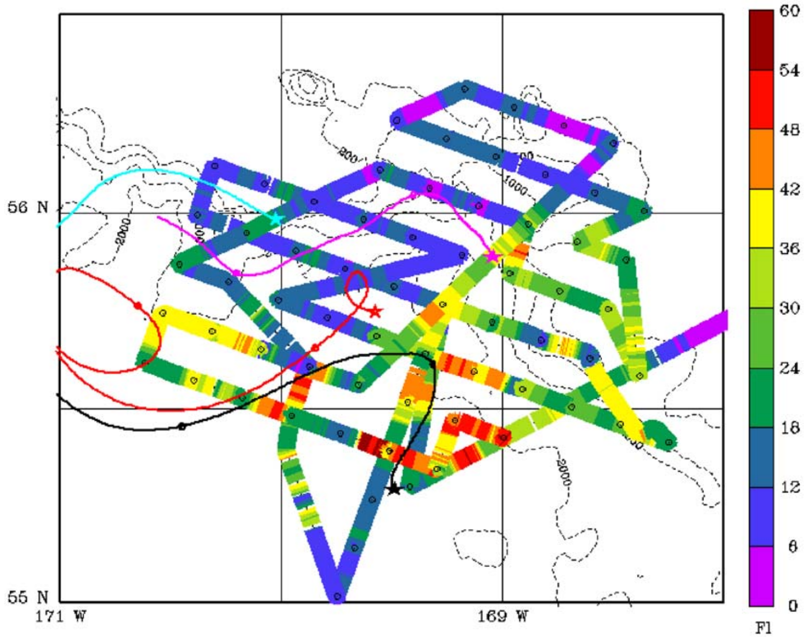

Fig. 18. Near-surface, relative fluorescence in the southeast Bering Sea over Pribilof Canyon, 31 May–8 June 2001, along the ship track as measured with a flow-through fluorometer. The uncalibrated fluorescence-plotting interval is 6 units. Isobaths are shown in black at 200, 500, 1000 and 2000 m. The 24-h-smoothed trajectories of four satellite-tracked drifting buoys are drawn as magenta, red, black and cyan curves.

2002 spring phytoplankton blooms. In the earlier bloom, anticyclonic eddies E1, E2, and E3 propagated along the continental slope while maintaining contact with the shelf-slope front (cf. Figs. 2, 5 and 6). In the latter bloom, eddies E13, E14, and E15 propagated along the continental slope while maintaining contact with the shelf-slope front (cf. Figs. 12, 15 and 16). In both years a relatively wide Green Belt was evident.

Conditions during the 2001 spring bloom in the northwestern Bering Sea were markedly different than occurred during the 2000 and 2002 spring blooms. The SSHA record showed that anticyclonic eddies E8 and E9 had moved off-slope prior to or shortly after the onset of the bloom (cf. Figs. 7 and 8). These eddies had low chlorophyll cores and high chlorophyll associated with their leading (off-slope) flanks. As a consequence, the 2001 Green Belt could be described as having two branches, one delineated by the shelf-slope front and one associated with the off-shelf flanks of the eddies.

The character of the Green Belt in the southeast Bering Sea east of 174°W was relatively similar during June 2000 and 2001 (cf. Figs. 6 and 11) as a result of there being fewer large eddies adjacent to the shelf at this time. In May 2002 eddy E15 was observed to be entraining chlorophyll from the shelf-slope region and diverting it off-slope.

The observations presented herein suggest that year-to-year variability in the character of the Bering Sea Green Belt (i.e. the distribution of chlorophyll) is related to the propagation characteristics of the BSC eddy field. In years which the eddy field propagates along-slope during the spring months, we might expect a Green Belt somewhat like that observed during the spring 2000 and 2002 phytoplankton blooms. In years which the eddy field propagates off-slope during the spring months, we might expect a Green Belt somewhat like that observed during the spring 2001 phytoplankton bloom.

SSHA along TOPEX orbital ground track D79 illustrate the interannual variability of the BSC

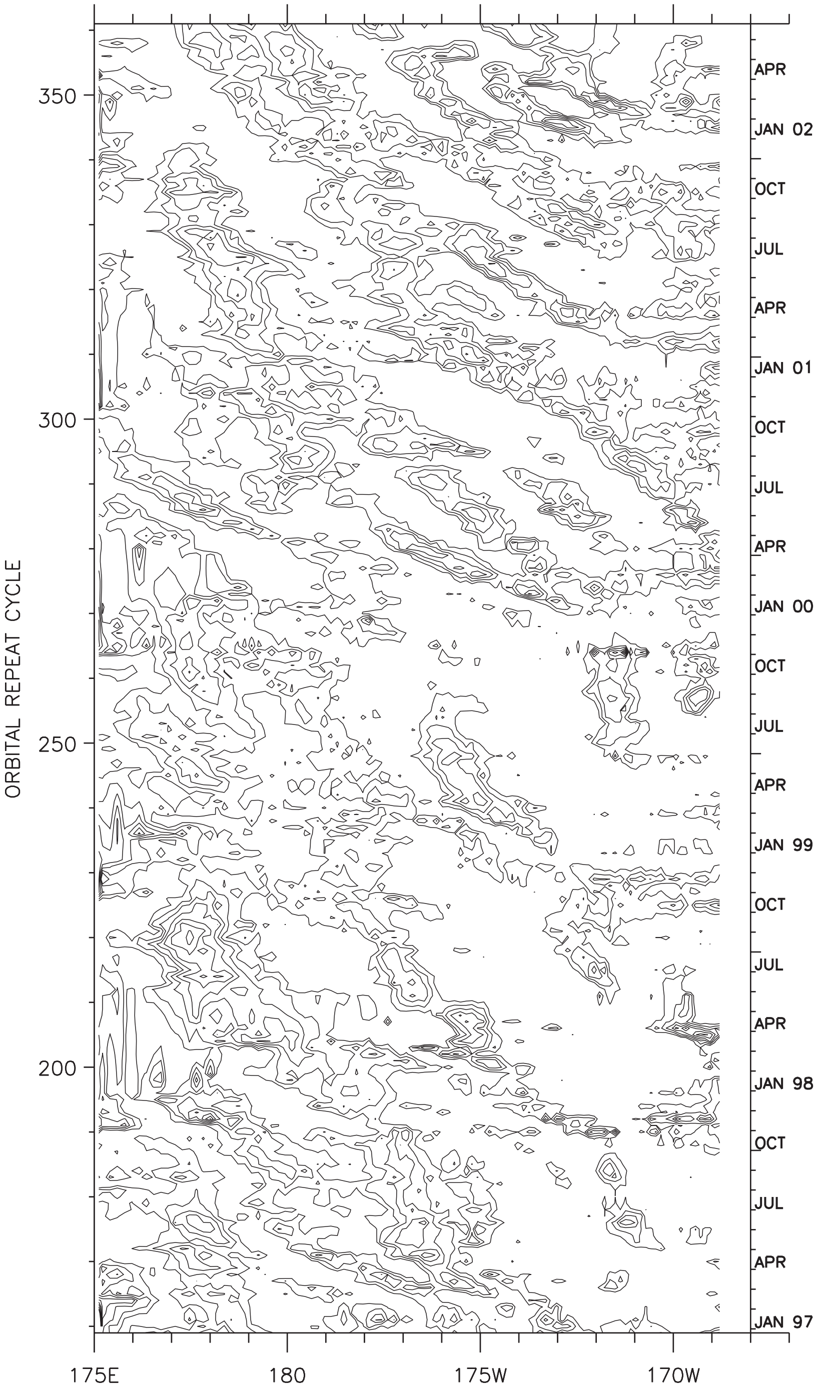

Fig. 19. Time-longitude plot of SSHA along orbital ground track D79 for the period January 1997–June 2002. For clarity, only positive anomalies are contoured. The contour interval is 4 cm.

eddy field for the period January 1997 through June 2002 (Fig. 19). SSHA along D79 for years 1993–1996 are given in Okkonen (2001). The 1998 and 1999 spring (April–June) eddy fields appear qualitatively similar to the 2001 spring eddy field in that there are fewer eddies and they exhibit slower along-slope propagation than occur in spring 1997, spring 2000, and spring 2002.

Because characteristically cloudy skies do not allow regular (periodic) satellite acquisition of Bering Sea chlorophyll imagery and shipboard surveys are spatially and temporally limited it is difficult to directly monitor seasonal and interannual variability of the chlorophyll concentration in the Bering Sea Green Belt. The observations and methods described in the preceding sections illustrate an indirect method, employing all-weather altimeter measurements of sea-surface topography, in conjunction with limited direct observations, by which the chlorophyll distribution near the margins of the deep Bering Sea (and other cloud-covered seas) might reasonably be inferred.

Acknowledgements

We thank Captain R. Parsons and the officers and crew of NOAA Ship *Ronald H. Brown* for a safe, productive cruise and D. Shields who designed the ship's Scientific Computer System. J. Shannahoff, C. DeWitt, W. Floering, S. Moreland, A. Childers collected CTD and water bottle data assisted by US Navy Midshipmen S. Heidt, C. O'Malley, T. Ray and A. Winberry as interns. The altimeter data were obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology. SeaWiFS imagery was provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE. This research was sponsored in part by the North Pacific Marine Research (NPMR) program and NASA. This paper is Fisheries Oceanography Coordinated Investigations (FOCI) contribution number B453-ROOP-0 and Pacific Marine Environmental Laboratory (PMEL) contribution number 2525.

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