JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, C05011, doi:10.1029/2006JC003899, 2007

Eddy transport of organic carbon and nutrients from the Chukchi Shelf: Impact on the upper halocline of the western Arctic Ocean

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Received 25 August 2006; revised 30 November 2006; accepted 8 December 2006; published 4 May 2007.

[1] In September 2004 a detailed physical and chemical survey was conducted on an anticyclonic, cold-core eddy located seaward of the Chukchi Shelf in the western Arctic Ocean. The eddy had a diameter of ∼16 km and was centered at a depth of ∼160 m between the 1000 and 1500 m isobaths over the continental slope. The water in the core of the eddy (total volume of 25 km^3) was of Pacific origin, and contained elevated concentrations of nutrients, organic carbon, and suspended particles. The feature, which likely formed from the boundary current along the edge of the Chukchi Shelf, provides a mechanism for transport of carbon, oxygen, and nutrients directly into the upper halocline of the Canada Basin. Nutrient concentrations in the eddy core were elevated compared to waters of similar density in the deep Canada Basin: silicate (+20 μmol L^{-1}), nitrate (+5 μmol L^{-1}), and phosphate (+0.4 μmol L^{-1}). Organic carbon in the eddy core was also elevated: POC (+3.8 μmol L^{-1}) and DOC (+11 μmol L^{-1}). From these observations, the eddy contained 1.25×10^9 moles Si, 4.5×10^8 moles NO_3^-, 5.5×10^7 moles PO_3^-, 1.2×10^8 moles POC, and 1.9×10^9 moles DOC, all available for transport to the interior of the Canada Basin. This suggests that such eddies likely play a significant role in maintaining the nutrient maxima observed in the upper halocline. Assuming that shelf-to-basin eddy transport is the dominant renewal mechanism for waters of the upper halocline, remineralization of the excess organic carbon transported into the interior would consume 6.70×10^{10} moles of O_2, or one half the total oxygen consumption anticipated arising from all export processes impacting the upper halocline.

Citation: Mathis, J. T., R. S. Pickart, D. A. Hansell, D. Kadko, and N. R. Bates (2007), Eddy transport of organic carbon and nutrients from the Chukchi Shelf: Impact on the upper halocline of the western Arctic Ocean, *J. Geophys. Res.*, *112*, C05011, doi:10.1029/2006JC003899.

1. Introduction

[2] The extensive continental shelf seas encircling much of the Arctic Ocean play a critical role in modifying and conditioning the waters of the interior basin. However, the precise mechanisms and rates by which water is transported off shelf remain largely unknown. One possible mechanism is via eddy formation at or near the continental shelf-break in the Chukchi/Beaufort Seas, in the relatively energetic peripheral currents, with subsequent migration into the central basin. This paper discusses the role that such eddies appear to play in the transport of carbon and nutrients into the Canada Basin, and some of the implications that this transport can have on the carbon budget, oxygen utilization, and maintenance of the upper halocline layer in the western Arctic Ocean.

1.1. Regional Hydrography, Biogeochemistry, and Eddy Properties

1.1.1. Regional Hydrography

[3] In the western Arctic Ocean, nutrient-rich Pacific and fluvial waters flow through Bering Strait into the Chukchi Sea where they undergo modifications through seasonal primary production, physical forcing (i.e., cooling in winter, densification through brine rejection) and interactions with the sediments [*Chen et al.*, 2004]. This area is subject to strong seasonal and interannual variability in sea ice cover, freshwater input from rivers, light availability and meteorological forcing.

[4] The volume transport through Bering Strait is on average 0.8 Sv (1 Sv = 10^6 m^3 s^{-1}), although this varies on a variety of timescales [*Roach et al.*, 1995; *Weingartner et al.*, 1998; *Woodgate et al.*, 2005]. On the eastern side of the strait, the inflow is dominated in late-spring to early-fall by the warm, relatively fresh Alaskan Coastal Current [*Paquette and Bourke*, 1974; *Mountain*, 1974]. The western

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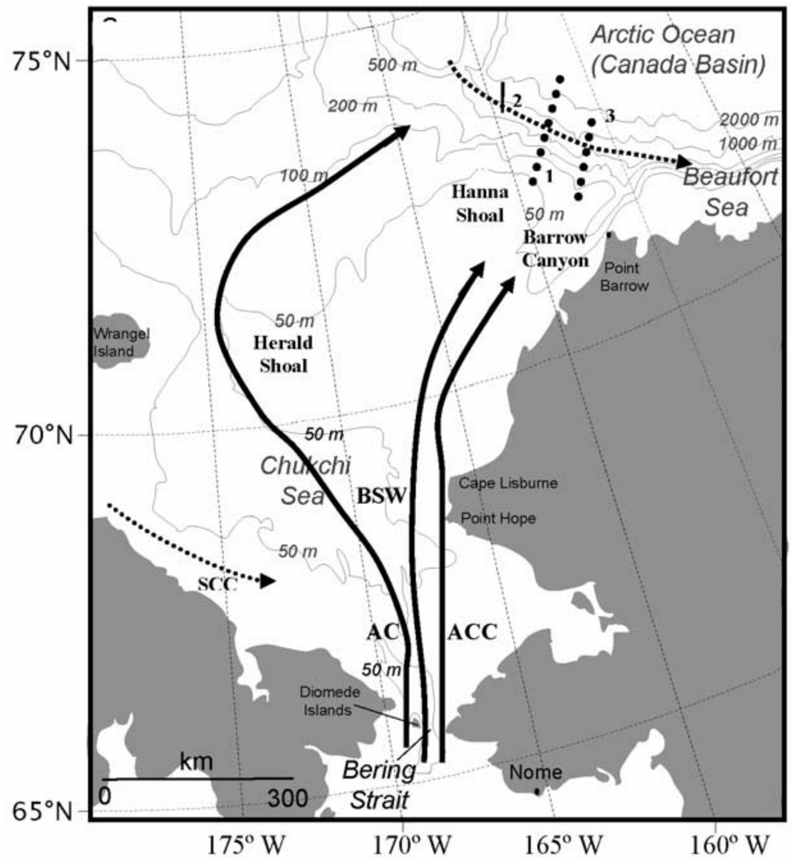

Figure 1. Map showing the flow of waters through Bering Strait (AC, Anadyr Current; BSW, Bering Shelf Water; ACC, Alaskan Coastal Current; SCC, Siberian Coastal Current) into the Chukchi and Beaufort Seas. The location of the shelf break current is indicated by the dashed line. Line 1, shelf-break transect line from the *Healy* cruise in summer 2002; line 2, transect line through the eddy occupied in 2004; line 3, shelf-break transect line from the *Polar Star* cruise in summer 2002.

side of the inflow contains water from the Anadyr Current, with the lowest temperatures, highest salinities and highest nutrient concentrations. The central Bering Strait contains Bering Sea shelf water that is intermediate in temperature and salinity. Observations suggest that water flows across the Chukchi Shelf as two or three distinct branches dictated by the bathymetry of the shoals and canyons [*Paquette and Bourke*, 1981; *Weingartner et al.*, 1998; *Woodgate et al.*, 2005], which is consistent with recent model results (M. A. Spall, Circulation and water mass transformation in the Chukchi Sea, submitted to *Journal of Geophysical Research*, 2006, hereinafter referred to as Spall, submitted manuscript, 2006) (Figure 1). North of Bering Strait some seasonal flow also enters the region from the East Siberian Current [*Muenchow et al.*, 1999], but it is not clear what impact this water has on the system (Figure 1).

[5] When the inflow through Bering Strait is reduced during winter due to intensified northerly winds, sea ice advances southward, covering the Chukchi Sea and parts of the Bering Sea. During this time, waters on the Chukchi Shelf are cooled and densified [*Weingartner et al.*, 1998], and the water entering the strait is also dense due to similar modification in the Bering Sea [*Muench et al.*, 1988]. Different classes of winter water are formed, and the largest volumetric mode on the Chukchi shelf is referred to here as "winter-transformed" Pacific water [see *Weingartner et al.*, 1998; *Pickart*, 2004]. At the end of winter, the newly formed dense water drains off the shelf [*Mountain et al.*, 1976; *Muenchow and Carmack*, 1997; *Pickart et al.*, 2005], and models predict that it should turn eastward as a shelf-break current along the edge of the Chukchi and Beaufort Seas [*Winsor and Chapman*, 2004; Spall, submitted manuscript, 2006].

[6] Recent observational studies indicate that such an eastward-flowing boundary current does indeed exist. In the Beaufort Sea a shelfedge current is present year-round, with distinct seasonal configurations [*Pickart*, 2004; A. Nikolopoulos and R. S. Pickart, The western Arctic Boundary Current at 152°W: Transport, structure, and variability, submitted to *Deep Sea Research, Part II,* 2006]. In late-winter to early-summer the current is bottom-intensified and advects winter-transformed Pacific water eastward. Some of this water likely emanated from Barrow Canyon [*Muenchow and Carmack*, 1997; *Pickart et al.*, 2005]. In the Chukchi Sea the situation is less certain due to limited observations. However, synoptic vertical sections across the continental slope suggest that a similar shelfedge current exists during the spring and summer months. For example, an absolute geostrophic velocity section occupied in early August 2002 on the *Polar Star* near 158°W shows winter-

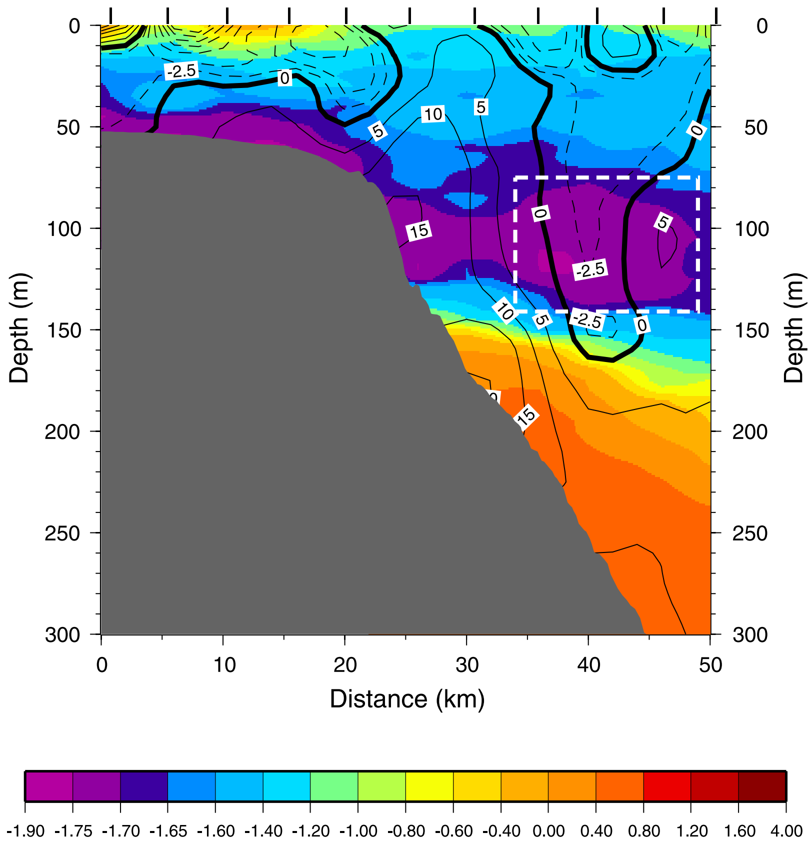

Figure 2. Shelf-break section of absolute geostrophic along-slope velocity (contours, cm s^{-1}) overlaid on potential temperature (color, °C) occupied in summer 2002 (line 3, Figure 1). The solid contours are eastward flow. The geostrophic velocity was referenced using lowered acoustic Doppler current profiler data [see *Pickart et al.*, 2005]. The anticyclonic eddy is located within the white dashed box. Station numbers are indicated at the top.

transformed Pacific water flowing eastward as a bottom-intensified current along the outer-shelf and shelf-break (Figure 2) [see also *Pickart et al.*, 2005]. The flow at 100 m depth is >15 cm s^{-1} and corresponds to a core of cold water <−1.7°C and elevated concentrations of silicate (not shown). Another absolute geostrophic velocity section occupied two months earlier at a nearby location showed a similarly configured boundary current (R. Pickart, personal communication, 2006). This is consistent as well with the temperature signal and density shear in historical hydrographic sections (e.g., see Figure 10 of *Weingartner et al.* [1998]). At other times of the year the flow along the shelfedge can be very different, and during upwelling winds the current can even flow to the west [e.g., *Muenchow et al.*, 2000]. However, in spring and summer, under light winds, the shelfedge current appears to flow eastward along both the Chukchi and Beaufort Seas.

1.1.2. Biogeochemistry

[7] As the winter-transformed Pacific water moves across the Chukchi shelf it is modified through chemical and biological processes from both the surface and from the sediments [*Cooper et al.*, 1997]. In late spring and early summer, when sea ice retreat exposes the nutrient-rich surface waters of the Chukchi Sea to sunlight, a brief but intense phytoplankton bloom occurs with rates of water column primary production >300 g C m^2 yr^{-1} [*Sambrotto et al.*, 1984; *Hansell et al.*, 1993; *Hill and Cota*, 2005], exhausting most of the nitrate in the surface layer. Some of the sinking particles are entrained or remineralized in the winter-transformed Pacific water and transported off the shelf [*Bates et al.*, 2005a, 2005b] while the rest are deposited in the highly productive sediments of the Chukchi Sea [*Moran et al.*, 1997; *Grebmeier and Dunton*, 2000]. Along with modifications from the surface, waters draining off the shelf are also modified through interaction with the benthos [*Moran et al.*, 2005; *Lomstein et al.*, 1989; *Grebmeier and Barry*, 1991; *Henriksen et al.*, 1993] and through stirring of the organic-rich sediments. The sediments of the Chukchi Sea are highly productive, and remineralized nutrients, dissolved organic carbon, and resuspended sedimentary particles are entrained by the overlying dense water as it moves northward [*Cooper et al.*, 1997] (Figure 3). When this modified water reaches the edge of the shelf, it gives the shelf-break current a strong biogeochemical "shelf signature" [e.g., *Pickart et al.*, 2005]. *Jones and Anderson* [1986] and *Moore et al.* [1983] suggested that nutrients released from Bering and Chukchi shelf sediments could play a role in the development of the Arctic Ocean nutrient maximum [*Aagaard et al.*, 1981; *Aagaard and Carmack*, 1989; *Jones and Anderson*,

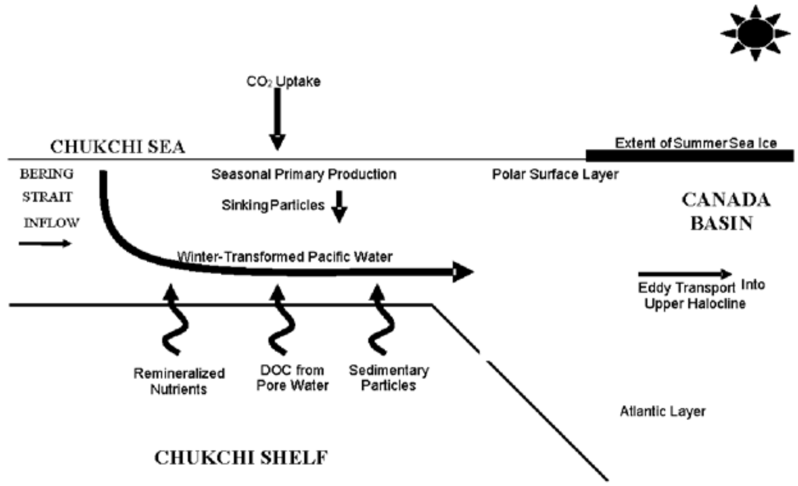

Figure 3. Modification of Pacific winter water as it crosses the Chukchi Shelf during spring and summer when biological activity is at its peak.

1986; *Macdonald et al.*, 1989; *Salmon and McRoy*, 1994; *Melling and Moore*, 1995] and organic matter transported from the shelf to the basin could drive down halocline O_2 concentrations.

1.1.3. Eddy Properties

[8] Seaward of the Chukchi and Beaufort Seas, the Canada Basin is populated with a large number of sub-mesoscale eddies [*Manley and Hunkins*, 1985; *Muenchow et al.*, 2000]. Most of theses eddies are anticyclones filled with Pacific-origin water, ranging in age from weeks [*Kadko et al.*, 2006] to a more than a year [*Muench et al.*, 2000]. It has been hypothesized that the eddies are formed at the mouth of Barrow Canyon [*D'Asaro*, 1988; *Chao and Shaw*, 2003], but recent observations suggest that they are formed along the entire length of the shelf-break, both to the east and west of Barrow Canyon [*Pickart et al.*, 2005; *Pickart*, 2005].

[9] A likely mechanism of formation is hydrodynamic instability of the eastward-flowing shelf-break jet, which was first hypothesized by *Manley and Hunkins* [1985]. *Pickart* [2004] showed that the springtime potential vorticity configuration of the current satisfies the necessary conditions for baroclinic instability, and Figure 2 shows an eddy of winter-transformed Pacific water being spawned from the current which supports this hypothesis. The lens of cold water (delineated by the white box in Figure 2) is circulating anticyclonically as it separates from the boundary. A similar pinching of boundary current water was observed during the same cruise on a section roughly 100 km to the east [*Pickart et al.*, 2005].

[10] Three types of eddies have been characterized in the southern Canada Basin from hydrographic and drifting-buoy observations. Warm-core surface-intensified eddies, containing Alaska Coastal Current water, have been observed in the vicinity of Barrow Canyon. These eddies seem to be seasonal (late-summer/early-fall), and are dissimilar to the eddy discussed in this study. The other two types of eddies are subsurface features that can have either a cold or a warm core As shown above, the former is spawned from the boundary current during spring and early-summer when the current is advecting dense winter-transformed water. The latter are formed later in the year (into autumn) when the boundary current has been replaced with warmer summertime Chukchi shelf water (R. Pickart, personal communication, 2006). The cold-core eddies are centered near a depth of 100–150 m, and are dense enough to provide a means for transport of Pacific-origin winter water into the upper halocline ($S = 33.1$; $T = -1.7°C$) of the Canada Basin. Hence, these eddies may play an important role in the maintenance of the halocline lying between the warm Atlantic layer ($S = 34.8$; $T = 0.4°C$) and the polar surface layer ($S < 30$; $T = -1.6°C$) [*Muench et al.*, 2000].

[11] In this paper we examine a cold-core, anticyclonic eddy surveyed just seaward of the Chukchi Sea in late-summer 2004, and compare its features to water in the boundary current from which the eddy was likely formed as well to those of a similar eddy that was observed in 1997 [*Muench et al.*, 2000]. Finally, we discuss the role that such eddies could play in the biogeochemistry of the Chukchi Sea and adjacent Canada Basin by estimating the off-shelf transport of nutrients and carbon, and the impact that this has on the basin interior.

2. Methods

2.1. Field Sampling

[12] Physical, chemical, and biological measurements were made from the USCGC vessels *Healy* and *Polar Star* during cruises to the Chukchi Sea in July/August, 2002 and from the *Healy* in September, 2004, as part of the Western Arctic Shelf-Basin Interactions (SBI) Program. During the cruises in 2002, physical and chemical measurements were taken at stations over the Chukchi Shelf, shelf-break, and deep Canada Basin, including dissolved and particulate organic carbon (DOC and POC). In 2004, an eddy was surveyed near the shelf-break of the Chukchi Sea.

[13] In Figure 1, line 1 was occupied in midsummer of 2002 onboard the *Healy* to provide background data on the structure of the water column over the shelf and shelf-break. Line 2 was a high resolution transect occupied through the center of the eddy in late-summer 2004 (see below for details). Line 3 shows the location of a shelf-break section occupied from the *Polar Star* in summer of 2002. During

the 2002 cruises the Chukchi Sea was mostly ice-free, but heavier ice was present at the outer edge of the shelf-break (>75%) and over the deep basin (>95%). During the 2004 cruise the shelf and slope (including the region where the eddy was situated) were completely ice-free.

2.2. Sample Analyses

[14] The instrument package on both cruises included a Seabird 911+ conductivity/temperature/depth (CTD) unit mounted on a 24-position frame with 10 liter Niskin bottles. Water for phosphate, nitrate, silicate, and nitrite analysis [*Codispoti et al.*, 2005] was collected throughout the water column and to within 1–2 m of the bottom. Standard CTD quality control was performed to produce 1-db average downcast temperature and salinity profiles.

[15] Samples for DOC and total dissolved nitrogen (TDN) analyses were filtered through inline precombusted GF/F filters held in acid washed polycarbonate filter holders. The filter cartridge was attached directly to the Niskin bottle with an acid cleaned and MilliQ® water rinsed silicone tube. Samples were collected into preconditioned and DOC-free, 60 mL HDPE bottles and frozen in organic solvent-free freezers, then shipped to the shore-based laboratories. All DOC/TDN samples were analyzed using the Shimadzu TOC-V/TN system. Extensive conditioning and standardization procedures were performed prior to analyzing samples each day. In addition, seawater DOC reference standards produced by the Hansell CRM program (http://www.rsmas.miami.edu/groups/organic-biogeochem/crm.html) were analyzed each day. To maintain the highest quality data control, samples were systematically checked against low carbon water and deep and surface reference waters every sixth analysis. The between-day precision in the DOC measurement was 1–2 μM, or a CV of 2–3%. Dissolved organic nitrogen (DON) values were determined by subtracting dissolved inorganic nitrogen (DIN) (DIN = NO_3^- + NO_2^- + NH_4) from the TDN (DON = TDN − DIN). The precision of DON is highly variable, and largely dependent on the amount of DIN present [*Hansell et al.*, 1993].

[16] POC concentrations were determined by drawing seawater directly from the Niskin bottles into Nalgene bottles. Known volumes (1–4 L) of seawater were vacuum filtered though a funnel array onto precombusted GF/F filters (25 mm Whatman, 0.7 μm pore size). Filters were then dried and placed into acid-washed precombusted scintillation vials, and stored until analysis. After acidification with HCL to remove inorganic carbon, the samples were analyzed for carbon using a Control Equipment Corporation (CEC) 240-XA Elemental Analyzer [*Knap et al.*, 1997].

3. Results

3.1. Chukchi Shelf-Break Section

[17] During the *Healy* cruise in summer 2002 several sections were occupied over the Chukchi shelf and shelf-break. We show one of these sections here (Figure 1, line 1) to provide context for the water in the boundary current, which is most likely the source of the core water of the observed eddy. The section had a tongue of cold ($T < -1.5$°C) winter-transformed Pacific water extending over the shelf-break and slope (Figure 4a). This water was colder than water of the same density in the interior Canada Basin and was most likely flowing eastward in the shelf-break current. Silicate concentrations were >40 μmol L^{-1} in the current (Figure 5a), and nitrate and phosphate concentrations were also highest in the same water mass with concentrations as high as 15 μmol L^{-1} and 2 μmol L^{-1}, respectively (Figures 6a and 7a). DOC concentrations at the shelf-break were ~70 μmol L^{-1} (Figure 8a). There was some indication of higher concentrations of DOC in bottom waters (not shown) over the shelf-break, indicating a possible efflux from the sediments. POC concentrations were highest over the shelf (>12.5 μmol L^{-1}) and lowest in the interior basin [*Bates et al.*, 2005a, 2005b].

3.2. Eddy Core Properties

[18] In September 2004 a cold-core eddy was observed northeast of Hannah Shoal (Figure 1, line 2) over the upper slope between the 1000 and 1500 m isobaths, centered at a depth of approximately 150 m (Figure 4b). The eddy was first located using expendable bathythermographs (XBTs), then a rapid high-resolution survey was carried out using a combination of CTDs and expendable CTDs along with the shipboard acoustic Doppler current profiler (ADCP). The grid was approximately 30 km on a side with 5 km resolution and took 24 hours to complete. This provided a three-dimensional snapshot of the eddy. Immediately following this, a section was occupied through the center of the eddy using the shipboard CTD package, including water samples. Figure 9 shows the grid of stations and a lateral view of the eddy's temperature field. It is clear from the figure that the CTD section passed through the center of the feature. The eddy radius was ~8 km, and the temperature at the core of the eddy was <−1.7°C. Dissolved oxygen (DO) concentrations inside the eddy core were 308 μmol L^{-1}, compared to 277 μmol/L outside the eddy in similar density water in the Canada Basin. The core density was 26.6 kg m^{-3} with a salinity of 33.1, indicating that the eddy was dense enough to ventilate the upper halocline of the interior Canada Basin.

[19] Concentrations of silicate, nitrate, and phosphate in the eddy core were elevated compared to offshore water in the Canada Basin and comparable to the values in the boundary current measured during 2002. Silicate reached >50 μmol L^{-1} inside the eddy core (Figure 5b), where the lowest temperatures (−1.7°C) were measured (Stations 124 and 125; Figure 4), while average nitrate and phosphate concentrations reached 18 μmol L^{-1} and 2.2 μmol L^{-1}, respectively (Figures 6b and 7b). The concentrations of dissolved organic nitrogen (DON) were ~5.5 μmol L^{-1} (not shown), representing about 21% of the total nitrogen in the core. Most of the nitrogen present in the eddy was in oxidized form (~68% nitrate). DOC concentrations were elevated within the cold core of the eddy (75 μmol L^{-1}) (Figure 8b), as were the concentrations of POC (4.6 μmol L^{-1}).

[20] Transmissometry showed particle enrichment in the eddy with the lowest transmissivity (83.7%) recorded near the eddy center (Station 125). Transmissometry outside the eddy at similar densities was consistently higher (>89.5%). This observation, along with the low $^{228}Th/^{228}Ra$ ratios in the eddy [*Kadko et al.*, 2006], is consistent with a near-

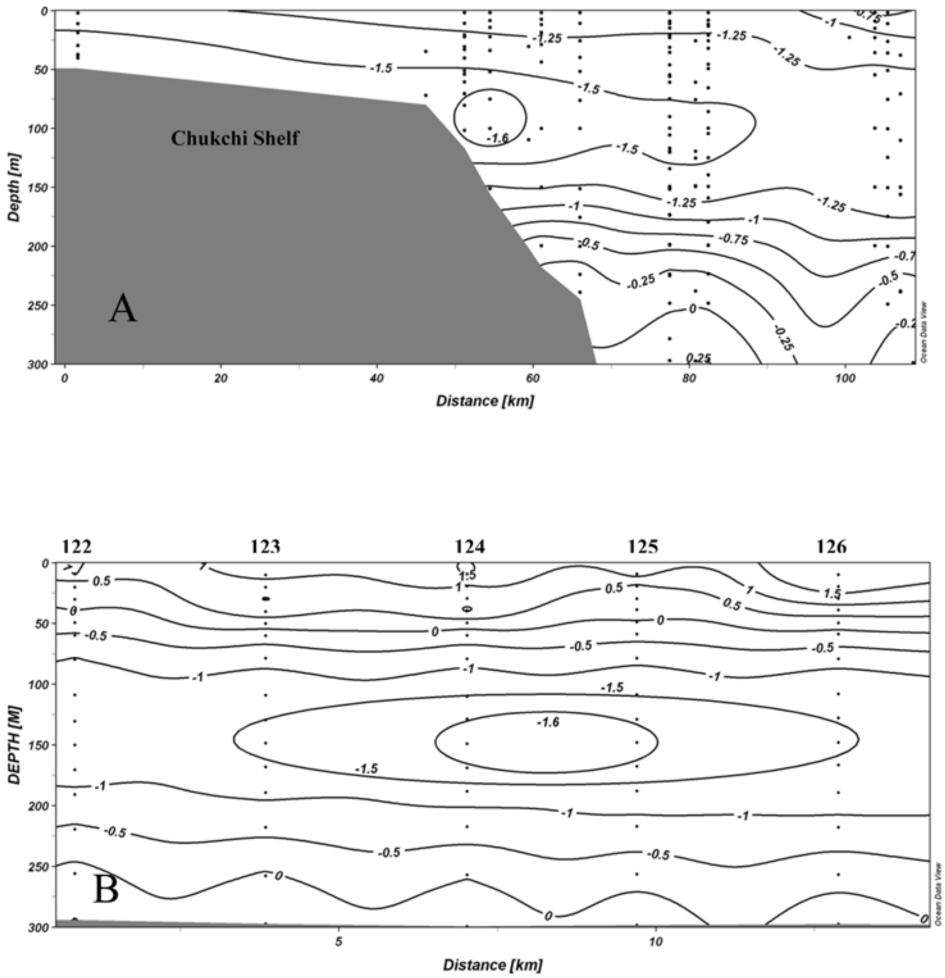

Figure 4. (a) Shelf-break section of temperature (°C) from summer section 2002 (line 1, Figure 1). (b) Temperature (°C) section across the eddy, 2004. Station numbers for 2004 survey are indicated at the top.

shore origin of the feature (Figure 10). *Kadko and Muench* [2005] have shown that the shelf and shelf-break waters of the SBI region contain low ^{228}Th/^{220}Ra ratios typical of most shelf environments [*Cochran et al.*, 1993].

4. Shelf-Basin Exchange by Eddy Transport

[21] Continental shelves comprise ~30% of the surface area of the Arctic Ocean and play a significant role in establishing property distributions within the Arctic Basin [*Aagaard et al.*, 1999]. Water conditioned at the continental margins is transported into the basin interior, bringing shelf material offshore and helping to maintain the cold halocline [*Aagaard et al.*, 1981; *Muench et al.*, 2000]. Numerous ideas have been put forth to explain how this lateral transfer might occur. Possible mechanisms include wind-forced upwelling/downwelling [e.g., *Aagaard et al.*, 1981; *Melling*, 1993], density-driven plumes through canyons [e.g., *Aagaard and Roach*, 1990], polynya-forced spreading [e.g., *Gawarkiewicz and Chapman*, 1995], and instability of boundary currents [*Manley and Hunkins*, 1985]. Recent evidence suggests that the latter mechanism, hydrodynamic instability and subsequent eddy formation (e.g., Figure 2), may be a dominant shelf-basin exchange mechanism in the western Arctic [*Pickart et al.*, 2005]. Here we consider the potential impact of eddies in the off-shelf transport of nutrients, particles, and shelf-fixed carbon.

[22] We must address two issues before determining the impact of eddies on the western Arctic basin. First, is the 2004 eddy representative of similar eddies found in the southern Canada basin? And second, how many eddies are formed in the region annually? To answer the first question, we compare the 2004 eddy to an eddy surveyed in 1997 [*Muench et al.*, 2000] (Table 1), and to answer the second question we examine the rate of eddy formation along the Chukchi/Beaufort shelf-break.

4.1. Comparison of the 2004 Eddy to One Observed in 1997

[23] The eddy surveyed in 2004 contained winter-transformed Pacific water of intermediate salinity (S = 33.1). The core was characterized by enhanced concentrations of nutrients, organic carbon, and particles, similar to water sampled in the shelf-break current (Figure 1), which was presumably the source of the eddy. The eddy appeared to be relatively young, with the water in the core having been isolated from the shelf for a period of months [*Kadko*

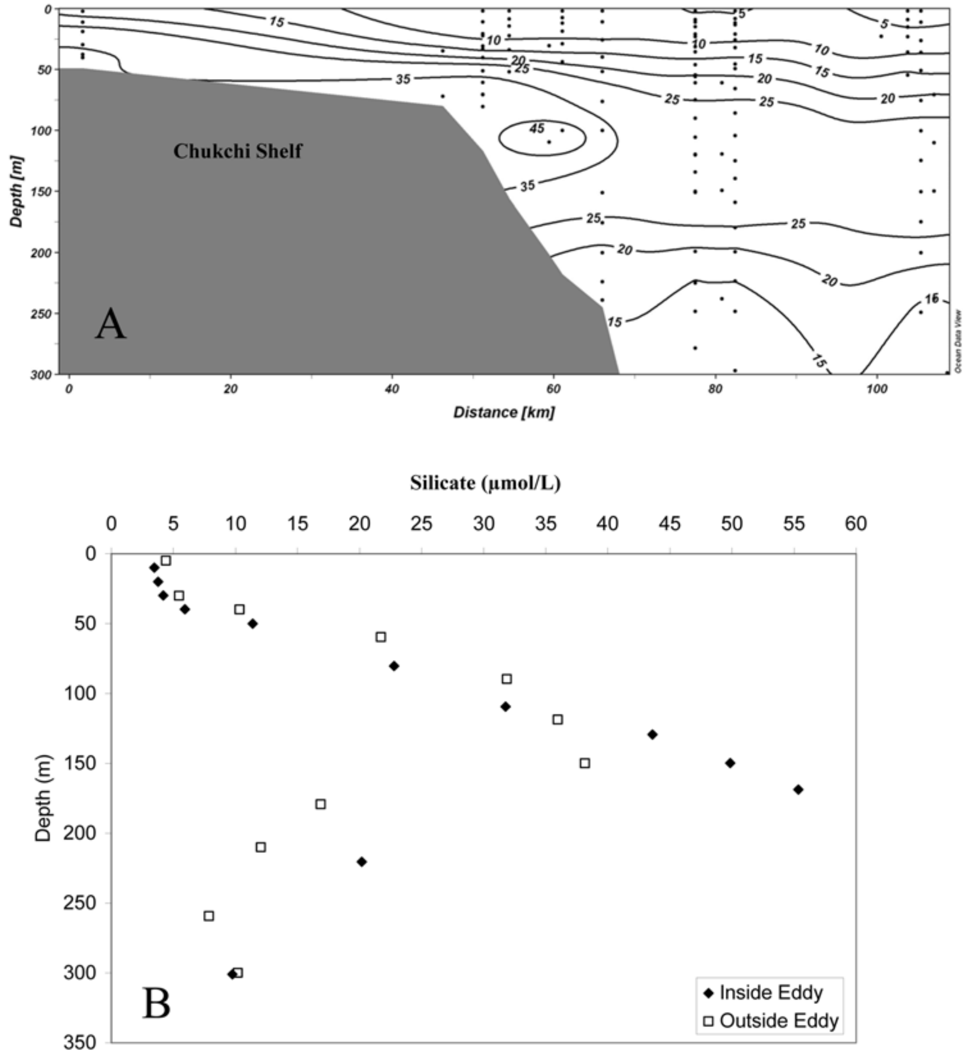

Figure 5. (a) Shelf-break section of silicate (μmol L^{-1}) from summer section 2002. (b) Silicate (μmol L^{-1}) distribution versus depth inside the eddy core and outside the eddy in the Canada Basin in 2004.

et al., 2006]. Inside the eddy core there was a load of suspended particles that were likely entrained from sediments as the dense Pacific water moved across the Chukchi shelf.

[24] Another cold-core eddy, similar to the one measured in 2004, was surveyed in the Canada Basin in September 1997 [*Muench et al.*, 2000]. The eddy observed in 1997 seems to have originated from the shelf-break current east of Barrow Canyon, while the 2004 eddy was likely formed west of Barrow Canyon [*Pickart et al.*, 2005]. Tracer data indicated the age of the 1997 eddy to be ~1 year [*Muench et al.*, 2000]. However, *Pickart et al.* [2005] suggest that this age estimate may be too high and that the eddy may have been only a few months old, making it more comparable in age to the relatively young eddy considered in this study.

[25] The 1997 eddy, located ~150 km north of the shelf-break in the Canada Basin, was also a cold core anticyclone (−1.75°C), with a radius of ~10 km and volume of 40 km^3. It had a central salinity of 33–33.5, similar to the 2004 eddy, indicating a Pacific origin (Table 1). The nutrient levels were similar as well to the 2004 eddy, thus providing evidence that there is consistency in the composition of these features.

4.2. Eddy Fluxes of Carbon and Nutrients

[26] The extent of the Canada Basin is taken here to be 10^6 km^2 and the thickness of the upper halocline to be 50 m [see *Pickart et al.*, 2005], giving the volume of winter-transformed Pacific water in the Canada Basin to be $\approx 5 \times 10^4$ km^3. It is believed that the renewal time of the upper halocline is on the order of 10 years [*Aagaard et al.*, 1981; *Carmack*, 1990] giving an annual renewal rate of 0.08–0.16 Sv [*Pickart et al.*, 2005]. If this renewal rate were driven entirely by eddies, then approximately 125 cold-core features would need to be formed each year from the shelf-break current, assuming that the eddies have an average radius of 10 km and a thickness of 75 m (volume = 25 km^3) [*Pickart et al.*, 2005]. Based on the preponderance of cold-core eddies measured during the SBI program (which had cruises in the months of May through October), we assume that most of the eddies in the interior basin contain cold,

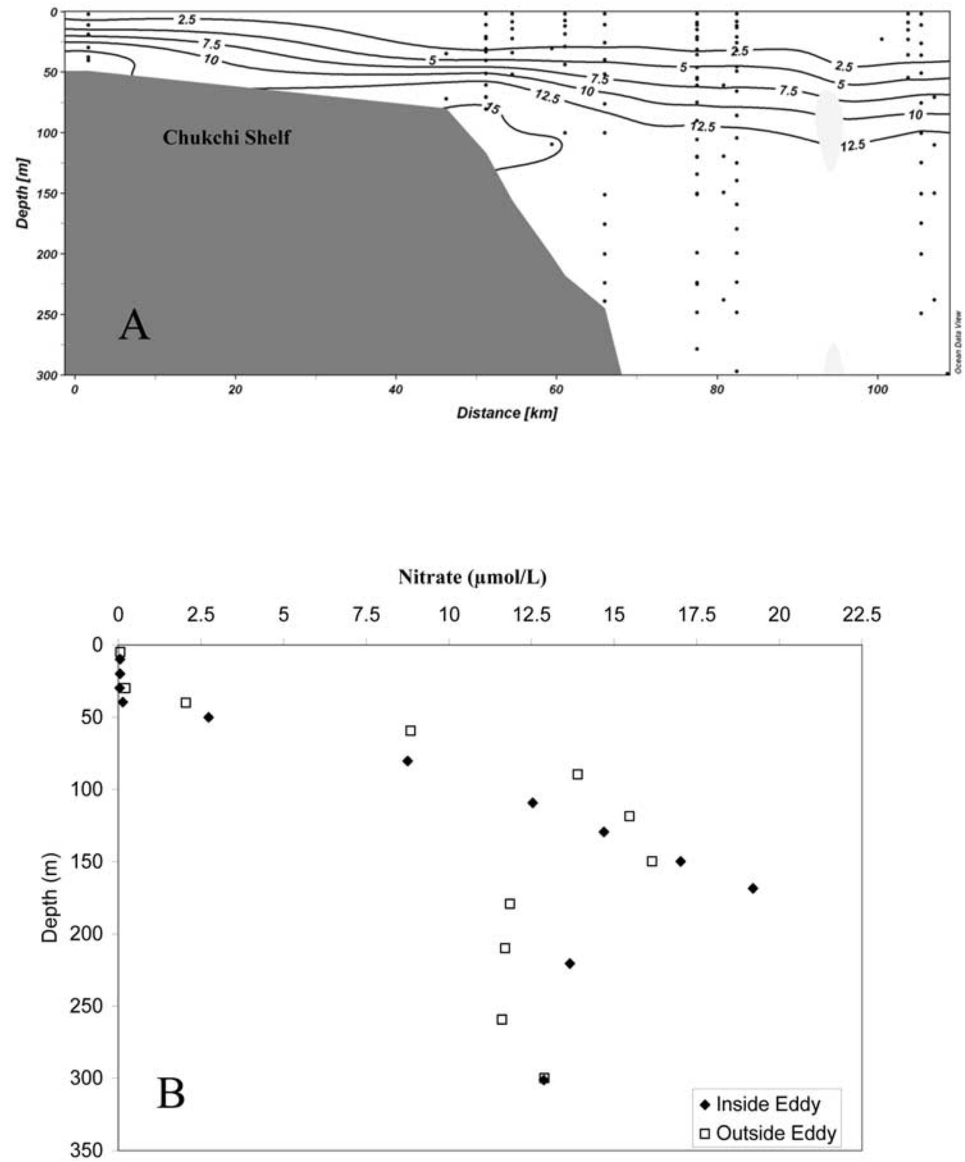

Figure 6. (a) Shelf-break section of nitrate (μmol L^{-1}) from summer section 2002. (b) Nitrate (μmol L^{-1}) distribution versus depth inside the eddy core and outside the eddy in the Canada Basin in 2004.

winter-transformed Pacific-origin water. During the AIDJEX experiment in the mid 1970s, *Manley and Hunkins* [1985] counted >100 subsurface eddies in the Canada Basin, indicating that the basin is densely populated with these features, and providing evidence for an active rate of formation. (It should be noted that that the four drifting ice camps in the AIDJEX program likely underestimated the true population of eddies in the basin.)

[27] Based on the average concentrations in the 2004 eddy core (Table 1) and its volume of 25 km^3, we estimated the inventory of shelf material available for transport into the Arctic Basin. Two stock calculations (total and net) were made in order to determine the effect that the eddy had on the removal of material from the shelf and to the overall impact on the Canada Basin (Table 2). The total stock was based on the total concentrations of carbon and nutrients in the eddy, and therefore represents the total amount of material that was being removed from the Chukchi Shelf. The net stock was based on concentrations of material in the eddy core in excess of water of similar density in the deep Canada Basin, and therefore shows the net impact that the transport of this core material would have on the upper halocline.

[28] The total stock of organic carbon (POC and DOC) in the 2004 eddy core was 2.02×10^9 moles-C. This organic carbon had entered the Chukchi Sea through Bering Strait, river input, interactions with the benthos, and the transformation of marine and atmospheric inorganic carbon during photosynthesis. The net stock of organic carbon in the eddy was 3.70×10^8 moles-C (9.43×10^7 moles-POC and 2.75×10^8 moles-DOC) (Table 2). This estimate is based on the carbon present in the eddy core in excess of water of the

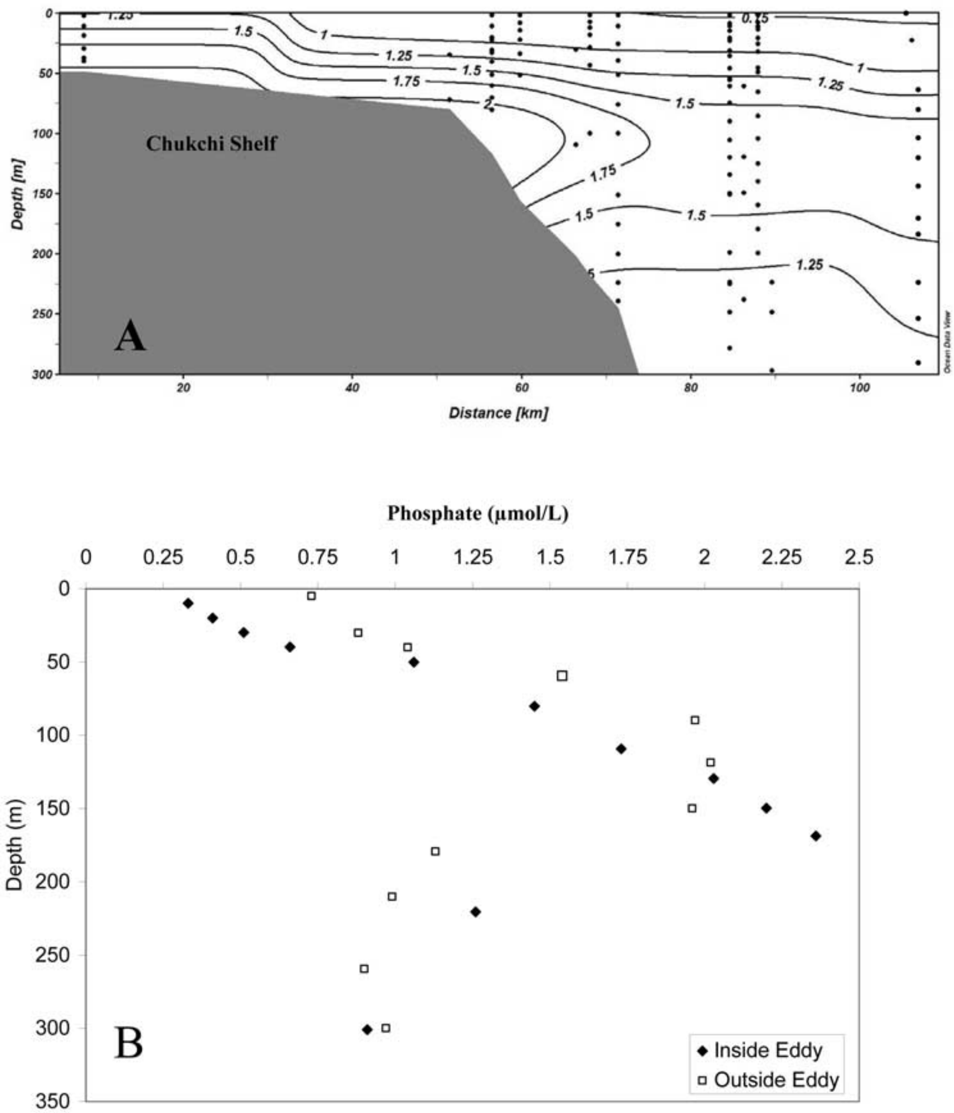

Figure 7. (a) Shelf-break section of phosphate (μmol L^{-1}) from summer section 2002. (b) Phosphate (μmol L^{-1}) distribution versus depth inside the eddy core and outside the eddy in the Canada Basin in 2004.

same density measured in the Canada Basin in 2002 (POC + 3.77 μmol L^{-1} and DOC + 11 μmol L^{-1}) (Table 1).

[29] If we assume that all of the cold-core eddies generated during spring and summer have concentrations of nutrients and carbon similar to the eddies observed in 2004 and 1997, and that such eddies are the dominant renewal mechanism in the western Arctic (i.e., ~125 eddies are formed each year), then eddies could remove 1.56×10^{11} moles-Si yr^{-1}, 3.52×10^{10} moles-NO_3^- yr^{-1}, 6.88×10^9 moles-PO_4^- yr^{-1}, 2.38×10^{11} moles-DOC yr^{-1}, and 1.44×10^{10} moles-POC yr^{-1} from the shelf. These nutrients are transported directly into the halocline and are at least partly responsible for maintaining the nutrient maxima that occur at this water depth for all three nutrients in the Canada Basin [*Anderson and Jones*, 1986].

[30] We cannot yet estimate transport in warm-core eddies due to the lack of biogeochemical data from such features. It seems likely, though, that these eddies would also transport material off the shelf. Even though the water in these eddies is warm compared with the ambient fluid in the Canada Basin, it may be dense enough to be in contact with the bottom as it crosses the Chukchi Shelf, thus picking up a sedimentary signature. Further work is needed in modeling and field observations to determine more accurately the number of warm eddies that are generated from the shelf-break current and to understand better the compositions of the water in the core of the eddies.

5. Potential Impact on Upper Halocline Biogeochemistry

[31] Mineralization of the organic matter transported into the upper halocline will impact concentrations of inorganic species and oxygen. For carbon, seasonal observations of

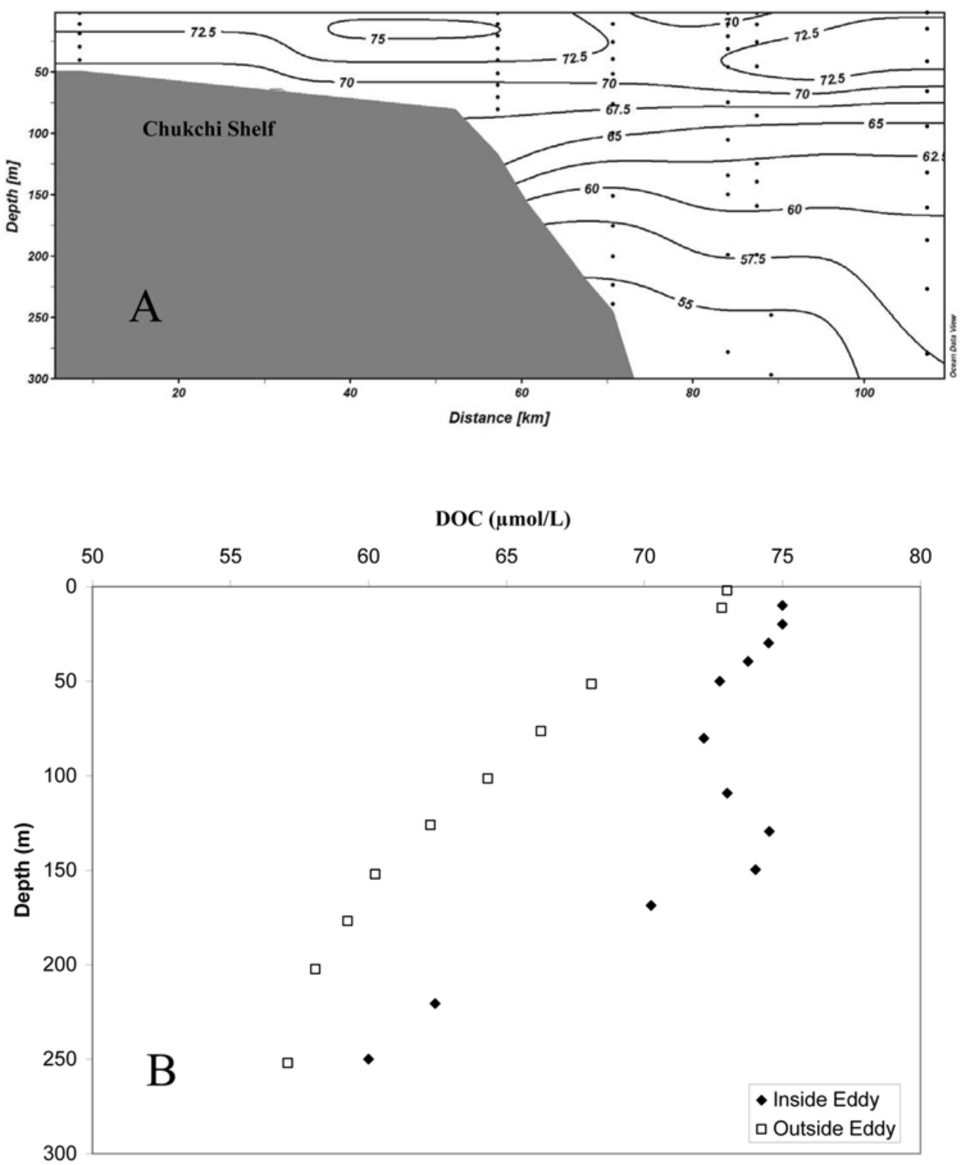

Figure 8. (a) Shelf-break section of DOC (μmol L^{-1}) from summer section 2002. (b) DOC distribution (μmol L^{-1}) versus depth inside the eddy core and outside the eddy in the Canada Basin in 2004.

the suspended POC pool indicated that there was a summertime subsurface accumulation of POC over the shelf and at the shelf-break in 2002 [*Bates et al.*, 2005a, 2005b]. Rates of net community production (NCP) in the region were spatially variable, ranging from 83–238 mmol C m^2 d^{-1} for the spring and summer growing season [*Bates et al.*, 2005a, 2005b]. Organic carbon entrained in the eddy is remineralized in the Canada Basin, increasing the dissolved inorganic carbon (DIC) concentrations in the upper halocline [*Bates et al.*, 2005a, 2005b] and reducing dissolved oxygen concentrations. Remineralization of the organic carbon occurs between spring and summer in the upper halocline [*Bates et al.*, 2005a, 2005b], supporting an active heterotrophic community.

5.1. Oxygen Utilization

[32] We can estimate oxygen consumption in the upper halocline arising from vertical export production plus the excess organic carbon transported horizontally in the eddies. For this calculation, we assume that all remineralization of vertically exported plus horizontally transported organic carbon takes place in the upper halocline [*Wallace et al.*, 1987; *Zheng et al.*, 1997]. We assume the C_{org}/-O_2 ratio of 117:170 by *Anderson and Sarmiento* [1994].

[33] Vertical export in the Arctic has been estimated by two approaches: using nutrient budgets in the surface layer and by oxygen utilization rates in the subsurface layer. *Anderson et al.* [2003] used phosphate deficits in the central part of the Canada Basin to determine vertical export

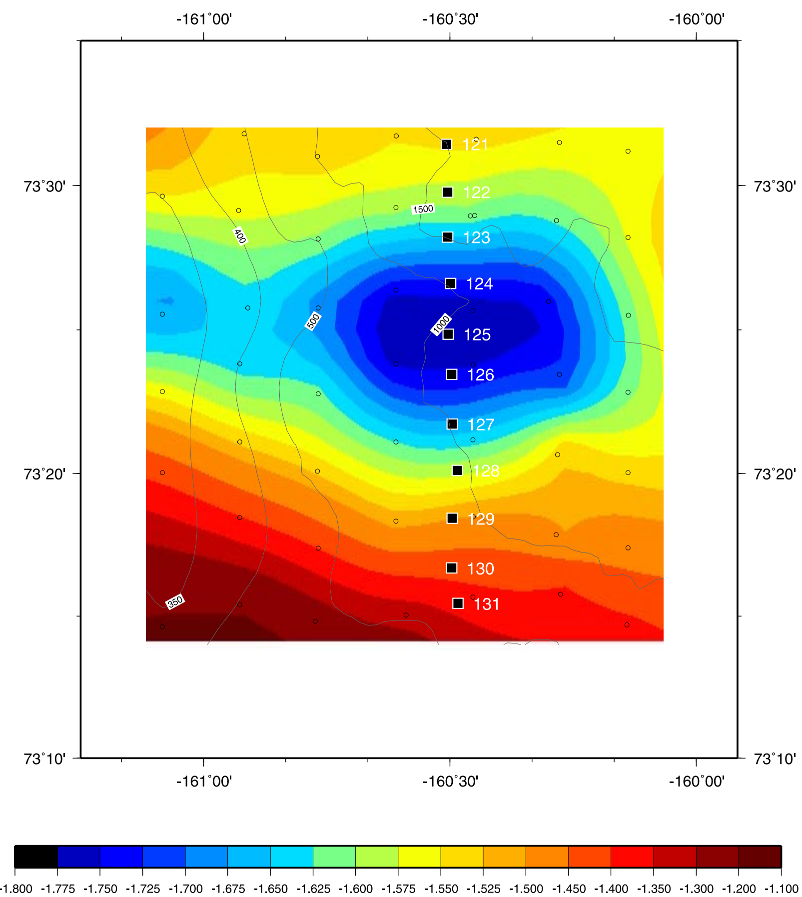

Figure 9. Lateral distribution of potential temperature (°C, color) between 125 and 185 m, associated with the cold-core eddy observed on the Chukchi slope (see Figure 1 for location of the eddy). The temperature is averaged between two depth horizons bracketing the core of the eddy. The data points from the expendable CTD survey are indicated by the small black circles. The CTD transect through the center of the feature is indicated by the black squares (along with station numbers). The bottom depth (in meters, measured by the ship's multibeam system) is contoured.

production to be, on average, <0.5 g-C m^{-2} yr^{-1} [*Anderson et al.*, 2003]. This estimate is supported by *Macdonald and Carmack* [1991], who used an empirical model of carbon flux based on ^{14}C ages and nutrient budgets of water in the deep Canada Basin, determining the vertical export flux also to be <0.5 g-C m^{-2} yr^{-1}.

[34] Calculations of vertical export production in the central Arctic Ocean based on apparent oxygen utilization rates (AOUR) have yielded much higher values (3–12.7 g-C m^{-2} yr^{-1}) [*Wallace et al.*, 1987; *Zheng et al.*, 1997]. The discrepancy between the higher export production rates based on AOU and the lower estimates of export production determined by other methods have led to the conclusion that rates of oxygen utilization are too high to be sustained by production in the central Arctic Ocean and therefore must be balanced by production over the Arctic Ocean continental shelves [*Zheng et al.*, 1997]. Our findings support the conclusion that a significant amount of organic carbon is being delivered horizontally to the upper halocline of the Canada Basin where is it remineralized, thus contributing to oxygen consumption.

[35] Here we use a mean export rate of 0.5 g-C m^{-2} yr^{-1} to calculate a total vertical export production over the Canada Basin of 4.2 × 10^{10} mole-C yr^{-1}. Assuming 125 cold core

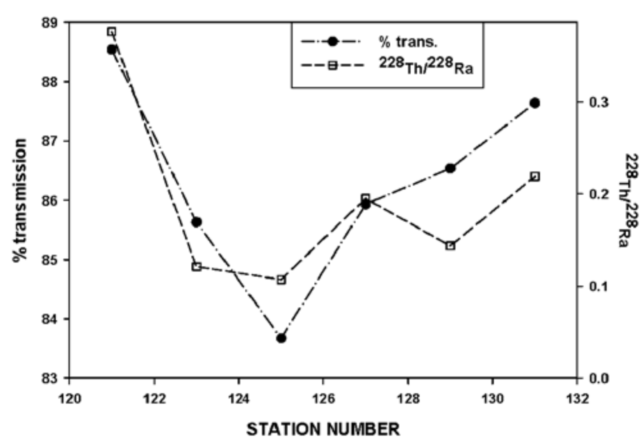

Figure 10. Distribution of transmissometry and ^{228}Th/^{228}Ra across the eddy at approximately 150 m depth (see Figure 3b for station locations). Station 125 was near the center of the core where the lowest temperature and highest particle load occurred.

Table 1. Properties and Composition of Eddies Surveyed in 2004 (This Work) and 1997 [*Muench et al.*, 2000], as Well as Comparison of These Features to the Average Values for Water in the Deep Canada Basin[a]

Eddy Core Properties	2004 Eddy	Canada Basin (2002)	1997 Eddy
Type	Cold Core	-	Cold Core
Rotation	Anticyclonic	-	Anticyclonic
Radius, km	8	-	10
Volume, km^3	25	-	40
Age	<1 month	-	~1 year
Density, kg/m^3	26.6	26.6	26.6
Temperature, °C	-1.70 ± 0.02	-1.57 ± 0.17	-1.75
Salinity	33.13 ± 0.07	33.1 ± 0.25	33.25
Dissolved Oxygen, μmol/L	308 ± 2.2	277 ± 11.08	~308
Transmissivity, %	83.7 ± 1.34	$>89.5 \pm 1.6$	-
Silicate, μmol/L	53.1 ± 2.7	33 ± 5.20	40
Nitrate, μmol/L	18.0 ± 1.27	13 ± 0.80	11
Phosphate, μmol/L	2.2 ± 0.08	1.8 ± 0.20	1.9
DON, μmol/L	6.1 ± 1.1	5.8 ± 2.45	45
DOC, μmol/L	76.2 ± 2.6	65 ± 6.31	-
POC, μmol/L	4.6 ± 0.06	0.83 ± 0.11	-

[a]Values for the 2004 eddy were determined by averaging data from stations 124 and 125 (Figure 3) in the density layer of 26.6 kg m^{-3}. Values for the Canada Basin were determined by averaging data in the density layer of 26.6 kg m^{-3} over the deep basin in 2004.

eddies each year and the net organic carbon (DOC and POC) transported in their cores, the net horizontal transport of organic carbon would be 4.6×10^{10} mole-C yr^{-1}. From this calculation, vertical export of carbon would account for 47% (6.1×10^{10} mol-O_2 yr^{-1}) of the oxygen utilization in the upper halocline, while the horizontal transport of organic carbon with eddies represents 53% (6.7×10^{10} mol-O_2 yr^{-1}) of the dissolved oxygen consumption. Because of the substantial amount of organic carbon transported horizontally into the Canada Basin with eddies, rates of vertical export production based on AOUR, without consideration of horizontal processes, are likely too high.

5.2. Upper Halocline Nutrient Maxima

[36] The nutrient maxima in the western Arctic Ocean coincides with the upper halocline, lying between 100 and 160 m depth and characterized by a central salinity of 33.1 [*Aagaard et al.*, 1981; *Aagaard and Carmack*, 1989; *Jones and Anderson*, 1986; *Macdonald et al.*, 1989; *Salmon and McRoy*, 1994; *Melling and Moore*, 1995]. The Pacific Ocean–derived waters of the upper halocline maintain the permanent stratification between the surface layer and underlying saline water of Atlantic origin in the Canada Basin [*Cooper et al.*, 1997], carrying nutrient-rich waters into the western Arctic Ocean. Therefore, the inflow of water through Bering Strait plays a role in controlling Arctic Ocean nutrient budgets [*Codispoti and Richards*, 1968] and in maintaining the stratification of the Canada Basin, which in turn promotes a hydrological regime that is conducive to sea ice formation and its associated climate and biogeochemical feedbacks [*Aagaard and Carmack*, 1989; *Rudels*, 1989].

[37] In spring and summer most of the nutrients that are carried into the Chukchi Sea with Pacific-origin water are consumed over the shelf by primary production. In winter, when primary production has ceased due to lack of sunlight, the flow through Bering Strait is greatly reduced [*Roach et al.*, 1995; *Woodgate et al.*, 2005], thus diminishing the transport of nutrients that could account for the observed nutrient maxima in the halocline of the Canada Basin. Therefore, it seems unlikely that nutrient-rich water from the Pacific has a direct and unaltered transit into the upper halocline of the Canada Basin. *Cooper et al.* [1997] described some of biogeochemical processes necessary in water flowing off the Chukchi shelf to contain the sufficient nutrient load to maintain the upper halocline nutrient maxima. In order for the shelf-break current and the cold-core eddies to contain the nutrient and carbon load observed, remineralization must occur in the sediments of the Chukchi Sea and these remineralized nutrients and organic carbon must be entrained in denser water as it moves over the shelf (Figure 3). Our data, both in the shelf-break current and in the 2004 eddy, support the findings of *Cooper et al.* [1997], strengthening the theory that winter-transformed Pacific-origin water contributes strongly to the nutrient maxima in the upper halocline and that eddies could be a significant mechanism for delivering this water into the interior of the Canada Basin.

[38] *Melling and Moore* [1995] showed that, occasionally, winter waters on the Mackenzie Shelf of the Beaufort Sea become sufficiently saline to ventilate the upper halocline of the Canada Basin. The low nutrient signatures carried into the halocline by these winter shelf waters would tend to erode, rather than reinforce, the nutrient maxima in the halocline. This winter-modified Mackenzie Shelf water cannot be the dominant source of water to the upper halocline [*Melling and Moore*, 1995], but it could mix with water from eddies that contain higher nutrient loads (such as the eddies evaluated here), thus maintaining the observed nutrient maxima in the Canada Basin.

[39] There is insufficient data to determine the extent to which each of these potential end members ventilates the upper halocline and contribute to the observed nutrient maxima, but our data suggest that cold core eddies generated along the Chukchi shelf-break contribute a significant nutrient load into the upper halocline and possibly represent the high nutrient end-member in the system.

6. Conclusion

[40] A detailed hydrographic survey has revealed the physical characteristics and biochemical makeup of a

Table 2. Total and Net Stocks of Carbon and Nutrients in the 2004 and 1997 Eddies[a]

Eddy Stocks	2004 Eddy Total	2004 Eddy Net	1997 Eddy Total	1997 Eddy Net
DOC, moles	1.90E + 09	2.75E + 08	-	-
POC, moles	1.15E + 08	9.43E + 07	-	-
DON, moles	1.53E + 08	7.50E + 06	1.80E + 09	1.57E + 09
Silicate, moles	1.25E + 09	5.00E + 08	1.60E + 09	4.00E + 08
Nitrate, moles	4.50E + 08	1.25E + 08	4.40E + 08	-
Phosphate, moles	5.50E + 07	1.00E + 07	7.60E + 07	4.00E + 06

[a]Net stocks were based on the average values in the eddy cores compared to those in the deep Canada Basin (Table 1).

cold-core, anticyclonic eddy located seaward of the Chukchi Sea shelf-break. The eddy was likely formed from the energetic shelf-break current, as suggested by previous work and by evidence presented here. Such eddies appear to play a significant role in transporting nutrients and carbon into the Canada Basin. We have shown the potential impact that this transport has on the removal of shelf-fixed carbon, the maintenance of the nutrient maxima observed in the upper halocline of the Canada Basin, and the utilization of dissolved oxygen in the deep Arctic Basin. This work further reinforces the importance that shelf processes play in conditioning the waters of the interior of the western Arctic Ocean.

[41] As the Arctic continues to warm in the coming decades, atmospheric forcing will change, sea ice cover and thickness will be reduced, and river runoff will provide an increased freshwater and nutrient flux to Arctic shelves. These changes could have dramatic effects on water chemistry, ecosystems, and human populations in the region. Further understanding of the interactions between the Arctic shelves and the deep basin is needed to understand these potential impacts.

[42] **Acknowledgments.** The authors would like to thank the officers and crew of the USCGC *Healy* for their tireless work in supporting these scientific cruises. We would also like to thank our SBI colleagues who were involved in collecting and analyzing the data presented here. This work was supported by the National Science Foundation, and office of Naval Research; DH OPP-0124900, NB OPP-0124868, DK OPP 0124872, RP N00014-02-1-0317.

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