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The Pribilof Islands: Temperature, salinity and nitrate during summer 2004

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ABSTRACT

The Pribilofs, comprised of St. Paul and St. George Islands and two smaller islands, are a highly productive area on the western edge of the eastern Bering Sea shelf. Proximity to both the slope and more shallow shelf waters, and the confluence of multiple physical domains differentiates conditions in this region from those in other areas on this shelf. This is a unique domain in the Bering Sea that we refer to as the "Pribilof domain". Hydrographic and biological data were collected during a 2004 summer research cruise in this region. The study undertook testing the hypothesis that on-shelf intrusion of slope waters supplies nutrients to this multi-domain area, thereby seasonally influencing new primary production and consequently the entire marine ecosystem. The Pribilof domain is characterized by enhanced mixing, particularly the area between St. Paul and St. George Islands; organized anti-cyclonic flow around St. Paul Island, around St. George Island, and around the island group; strong tidal currents; and is a location where nutrient-rich water from the bottom layer of the middle shelf and deeper water from the slope are vertically mixed to sustain production throughout the summer.

1. Introduction

The Bering Sea is a marginal ice zone with a broad eastern shelf extending >500 km westward from the Alaska coast, a central oceanic basin, and a narrow western shelf. The eastern shelf comprises approximately half of the area of the Bering Sea (Fig. 1). The productive shelf-edge front between the Bering Sea basin and continental shelf is known as the "green belt" (Springer et al., 1996). The Pribilof Islands are the center of a productive region where multiple hydrographic domains converge (Hunt and Stabeno, 2002; Macklin et al., 2002). Biota in the Pribilofs region are abundant, with a large fishery, shellfish resources, and summer influx of marine mammals and seabirds. Interannual variability in annual sea ice strongly influences shelf water structure and setup for the year's production cycle over the eastern shelf (Stabeno et al., 1999).

From May to October, the southeastern Bering Sea cross-shelf hydrography is characterized by three domains (Fig. 2) maintained by a balance of wind and tidal mixing. The inner or coastal domain occupies the space between shore and ~50 m depth and is well mixed or weakly stratified due to wind and tidal mixing. The middle domain, between ~50 and ~100 m isobaths, consists of a two-layer system with a top layer of warmer, often slightly fresher water overlaying a colder, more saline bottom layer separated by a sharp thermocline. Tidal currents mix the bottom layer, while the upper layer is mixed by winds. The depth of thermocline varies both seasonally and interannually, and typically ranges from 20 to 35 m (Coachman, 1986; Kinder and Schumacher, 1981; Schumacher and Stabeno, 1998). The inner and middle domains are separated by the inner front which is a transition zone 5–20 km wide found near the 50 m isobath (Schumacher et al., 1979; Stabeno et al., 2001; Kachel et al., 2002). The outer-shelf domain extends between the ~100 and 180 m isobaths, with a wide (>50 m) middle transition zone separating it from the middle-shelf domain. The shelf-break front separates the outer domain from the basin.

The Pribilof Islands sit in the middle transition zone at the convergence of the middle-shelf and outer-shelf domains. While this island area is similar to the coastal domain in depth and water-column structure (Stabeno et al., 1999), it has some marked differences. This hybrid region is influenced by both the middle- and outer-shelf domain and by the shelf slope. We will refer to this region as the Pribilof domain (Fig. 2).

In the summer of 2004, a multidisciplinary research cruise focused on the area around the Pribilof Islands (Fig. 2). The goal was to expand our understanding of this region through investigation of the mechanisms that control on-shelf flow and bottom-up processes on the shelf, and their influence on production and ecosystem processes. This article delineates hydrographic and nutrient (nitrate) data collected during this

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cruise, presented in the context of the tidal, wind and current conditions in the region of the Pribilof Islands. All cruise data sites are shown for context (Figs. 1 and 2), and we examine selected hydrographic lines for cross-shelf and cross-domain patterns, comparing them to moored time-series data from a representative mooring, P1, located between St. Paul and St. George Islands (Fig. 1). Additional mooring data are discussed in Stabeno et al. (2008).

We begin with a discussion of the flow around the islands and trends for 2004, then focus on cross-shelf structure in temperature and nitrate at three hydrography lines. Next we discuss changes during several occupations of the transect between St. Paul and St. George Islands. Finally, we examine how water properties were modified as water was advected around St. George Island.

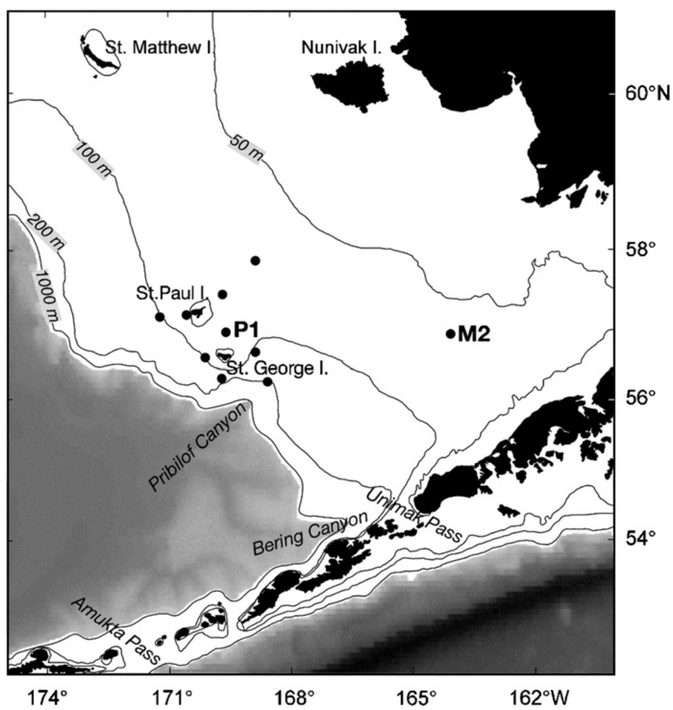

Fig. 1. Map of the eastern Bering Sea shelf showing place names, isobaths, and mooring locations. Reference is made to long-term mooring M2 and Pribilofs P1 mooring.

2. Methods

Conductivity, temperature, and depth (CTD) data were collected on the Bering Sea shelf in the vicinity of the Pribilof Islands during a summer research cruise on the R/V *Alpha Helix,* HX288. Between July 26 and August 19, 2004, a total of 289 hydrographic casts were completed. Dual temperature and conductivity profiles were recorded using a Seabird 911-Plus CTD. In addition, fluorescence and photosynthetically activated radiation (PAR) were recorded on each cast.

Most casts were $<$120 m depth, though on the shelf-slope edge, some casts were up to 600 m. Water samples for nutrients were collected from Niskin bottles at 10 m intervals on each cast, and water samples for bottle salinity were taken every other cast for calibration. The CTD rosette was lowered to 10 m then brought back to the surface to begin the profile. Descent rates were 15–30 m/min. Data were reviewed and spurious points were removed. We emphasize temperature since it determines vertical structure during the summer on the Bering Sea shelf (Kachel et al., 2002). CTD instruments were calibrated by the manufacturer pre- and post-cruise.

Nutrient samples were analyzed for dissolved phosphate, silicic acid, nitrate, nitrite and ammonium using protocols of Gordon et al. (1993); however, only nitrate will be discussed in this manuscript. Discussion of nutrients (Sambrotto et al., 2008) and ammonium (Mordy et al., 2008) are contained within this issue. Samples were collected in 50-ml high-density polyethylene bottles that were rinsed first with 10% HCl prior to each station, and rinsed at least three times with sample before filling. Some samples were refrigerated for 3–12 h prior to analysis. Nitrate was analyzed using a Perstorp auto analyzer modified with Alpkem RFA 300 mixing coils.

Mooring P1 was deployed on April 30, 2004 at 56.90°N, 169.59°W, and recovered on October 1, 2004 (Fig. 1). Multiple

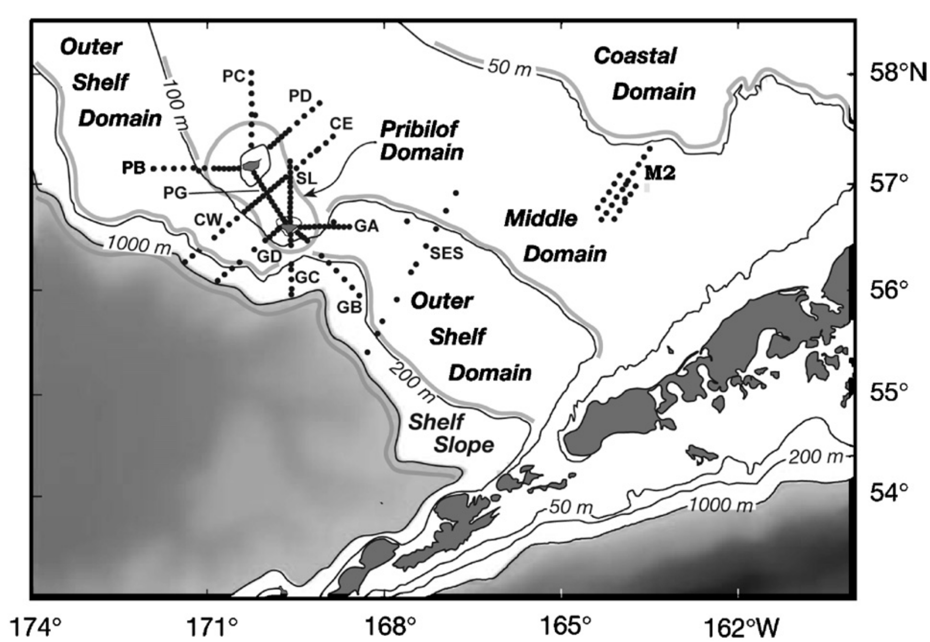

Fig. 2. Eastern Bering Sea shelf hydrographic domains: Coastal, Middle, Outer Shelf, Pribilof and Shelf Slope. CTD stations on the shelf and around the Pribilof Islands are indicated by dots. Labels indicate transect lines.

moorings were deployed and recovered within the same time frame to characterize currents in the area (Stabeno et al., 2008: Table 1 for moorings information, Table 3 for mooring velocity statistics). On P1, temperature was recorded at eight depths (depths: 12, 13, 18, 23, 28, 33, 43, 57 m) throughout the water column, salinity was recorded near-surface at 12 and 13 m, and near-bottom at 57 m, a fluorometer was placed near 12 m, and an upward-looking Acoustic Doppler Current Profiler (ADCP) was located at ~62 m.

3. Results/discussion

Data were collected on the July–August, 2004 R/V *Alpha Helix* cruise around the Pribilof Islands, and on the middle shelf near M2, a long-term biophysical mooring (1995–present). M2, at the center of the middle shelf, provides a contrast to the more dynamic Pribilof domain. The extended region around the islands encompasses a complex area influenced by converging domains, currents, seasonal winds, bathymetry and tides. This manuscript will focus on selected CTD sections around the Pribilof Islands (Fig. 2) that are divided into three groups. The first group consists of three cross-domain transects that extend in a generally east to west direction across the study area, and show a snapshot of cross-shelf water-column structure at varying latitudes: a northern transect near St. Paul Island, a central transect between islands, and a southern transect near St. George Island. The second group of transects is a line between St. Paul and St. George which was replicated four times over the duration of the cruise. The final group is the set of four transects that radiate from St. George Island.

3.1. Mean circulation

A portion of the Alaska Coastal Current (Stabeno et al., 2004) flows through Unimak Pass onto the Bering Sea shelf, where it combines with water flowing up Bering Canyon. This flow bifurcates, with a portion following the 50 m isobath and the remainder following the 100 m isobath (Schumacher and Stabeno, 1998; Stabeno et al., 2002). The northwestward flow along the 100 m isobath is enhanced both by an influx of water from instabilities in the Bering Slope Current (BSC) (Stabeno and van Meurs, 1999), and by flow up both lobes of Pribilof Canyon near St. George Island (Stabeno et al., 2001, 2008). Coachman (1986) suggested that as the distance between 100 m and 200 m isobaths decreases from ~160 to <30 km near Pribilof Canyon, the flow accelerates. This constriction of isobaths occurs south of St. George Island. Typically the flow continues along the 100 m isobath intensifying over this narrowing shelf; however, sometimes a weaker, less organized flow continues along the east side of St. George Island, where it dissipates (Stabeno et al., 2008).

A map of Lagrangian current velocities was derived from satellite-tracked drifters that transited this area between 1985 and 2005 (Fig. 3, from Stabeno et al., 2008). These drifters were drogued at 40 m. The BSC is evident in the vectors along the shelf break. Over the middle transition between Pribilof and outer-shelf domains, the flow generally is northwestward, paralleling the 100 m isobath. From this middle transition flow, anti-cyclonic circulation occurs around each island and also around the island group. The combined signature of these anti-cyclonic flows around the Pribilof Islands roughly parallels the estimated shape of the Pribilof domain (Fig. 2).

While the BSC has a consistently higher velocity, the highest average velocities over the shelf (exceeding 40 cm s^{-1}) occur in two places: in close proximity to the islands, as a result of tidal rectification, and south of St. George, where the flow is confined to the narrow shelf. Currents continuing along the 100 m isobath northwest of the Pribilof Islands are slower and spread out.

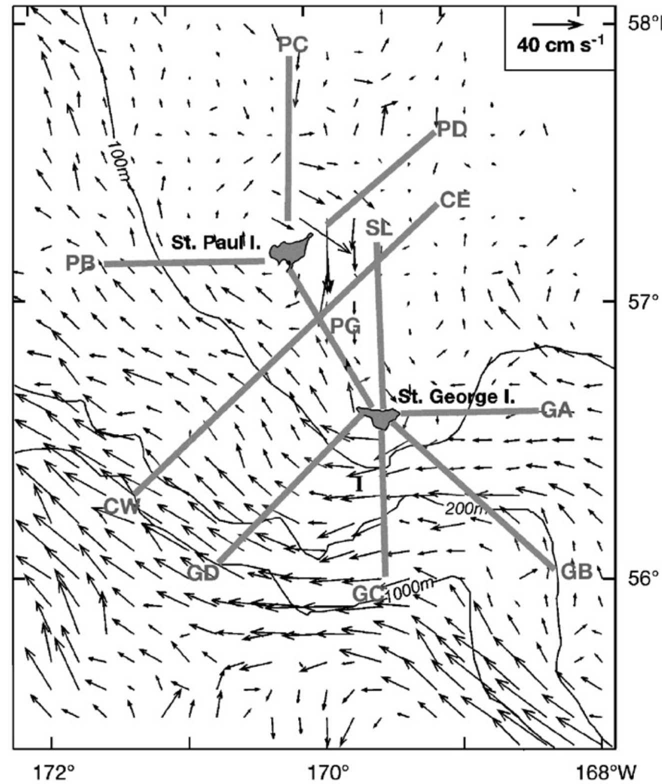

Fig. 3. CTD transect lines overlay a composite (1985–2005) of Lagrangian currents at ~40 m using satellite-tracked drifter trajectories (Stabeno et al., 2008).

3.2. General middle-shelf trends, 2004

The climate trends of three preceding years over the middle-shelf domain continued in 2004 (Stabeno et al., 2007) with sparse winter and spring ice cover, early warming, and early stratification in the middle domain. Although this study was conducted in summer, consideration must be given to earlier ice conditions as it has been argued that spring ice conditions determine hydrographic structure throughout the summer (Stabeno et al., 2001). According to long-term temperature data and ice charts, no ice-coverage was seen at mooring M2 on the southeastern shelf during 2004 (Stabeno et al, 2008). The well-mixed, winter water column at M2 evolved into a two-layer system with surface heat mixing down to a depth of 20–25 m by early May. Surface mixed-layer temperatures reached a maximum of >13 °C during August. Ice did not reach as far south as the Pribilof Islands during the winter of 2003–2004.

3.3. Cross-shelf transects

Three cross-shelf hydrographic transects passed through multiple domains in the Pribilof Islands region (Fig. 2). These transects, PBPD, CWCE and GDGA, revealed the water column structure at St. Paul Island, between islands, and at St. George Island, respectively (Figs. 4 and 5).

We will start with the center transect, CWCE, which extended from the shelf slope northeastward to the middle domain, crossing between St. Paul and St. George Islands. CW was measured over a 14 h period on August 3–4, and CE over an 8.5 h period on August 4–5. To the east is a classic two-layer,

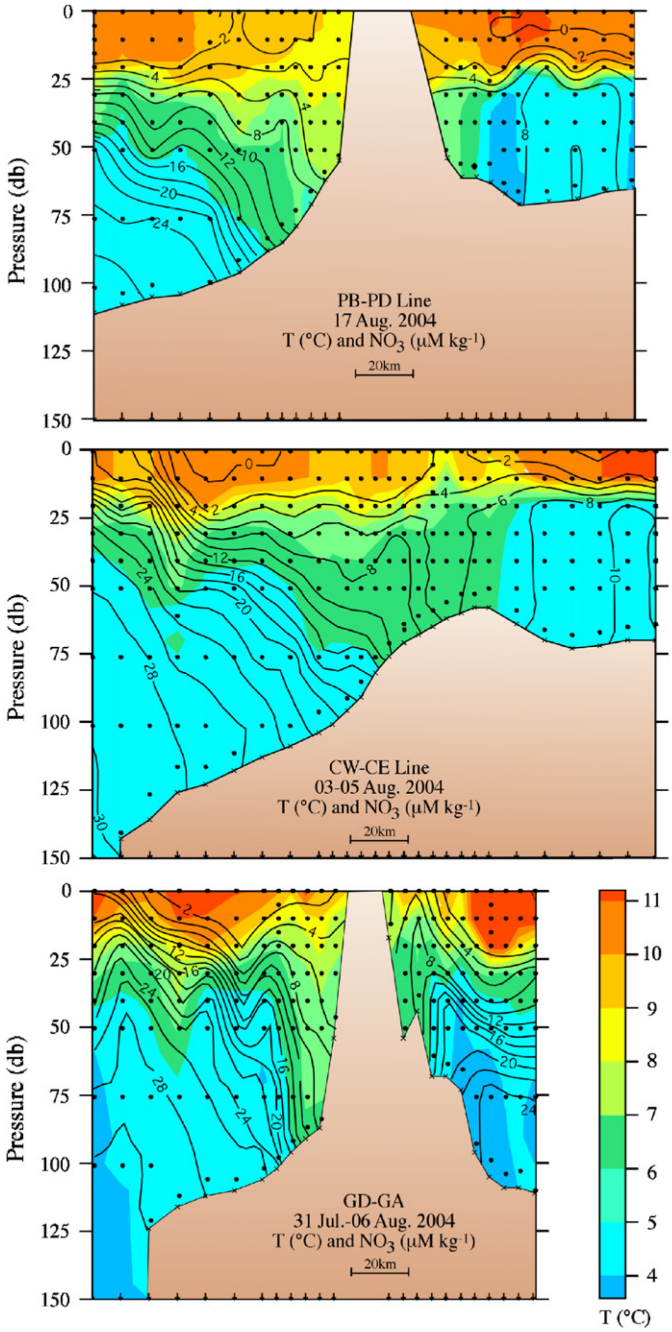

Fig. 4. Contour plots of temperature (colors) and nitrate (lines) across the shelf illustrating data along three transects, from north to south: PBPD, CWCE, and GDGA. Nitrate depths are indicated by dots.

middle-shelf domain structure with a ~20 m surface mixed layer (Fig. 4, middle panel, Fig. 5). This warmer, fresher upper layer (10.2–11.2 °C, ~31.9 psu) was depleted of nitrate, while the colder, saltier bottom layer (~4.2 °C, >32.1 psu) had moderate nitrate concentrations.

As the CWCE line crossed into the Pribilof domain (at ~145 km), the thermocline weakened. Heat from the surface layer mixed down, while salt and nitrate were mixed upward by the strong tidal currents (Stabeno et al., 2008). The Pribilof domain was more mixed than the middle shelf, but not as well-mixed as the more uniform water column of the coastal domain (Kachel et al., 2002), this is largely due to the fact that the coastal domain is shallower (<50 m). Temperature in the Pribilof domain ranged

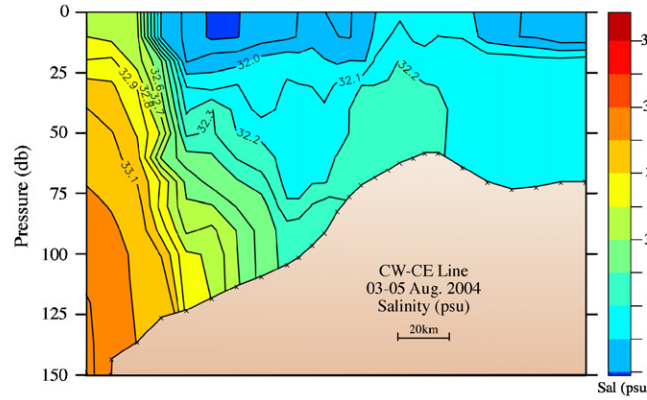

Fig. 5. Cross-shelf contours of salinity along CWCE transect.

from <10 to ~5 °C; salinity from ~31.9 to 32.25 psu; and nitrate concentrations from 2 to 8 μM kg^{-1} (surface to bottom). Shallower depths and stronger tidal mixing reduced stratification, thus decreasing temperature, and increasing salinity and nitrate in the upper water column. The continuous upward mixing of nitrate to the surface in this domain sustained new production throughout the summer (Sambrotto et al., 2008), and distinguished it from the two-layered middle-shelf domain. The source of this more saline, nutrient-rich bottom water is twofold: the bottom layer of the middle shelf, and the slope (Stabeno et al., 2008).

The remainder of the transect extended west to the shelf slope. Temperatures were 5–6 °C near ~50 m, with less stratification than in middle-domain waters. Surface temperatures were slightly cooler than those of the middle domain or outer shelf. The shelf-break front shows a strong salinity gradient. At ~75 m depth, cool, salty, nutrient-rich slope water had salinities as high as 33.4 psu and nitrate concentration of 28 μM kg^{-1}. Outcropping of higher nitrate (4–10 μM kg^{-1}) at the surface at the shelf break supports higher production along the shelf-break "green belt" (Springer et al., 1996).

The northern-most of the three cross-shelf transects (PBPD) extended from the middle domain westward to the outer-shelf domain (Fig. 4, top panel). PB and PD were sampled on August 17 as two transects of 6.5 and 5.75 h in duration, respectively. Northeast of St. Paul, the well-defined two-layer structure of the middle shelf had a mixed-layer depth of 20–25 m (Fig. 4, top panel). Due to a recent storm, the mixed-layer depth here was deeper and the surface layer slightly cooler (10.6–11.0 °C) than on the central (CWCE) transect (Stabeno et al., 2008). Near the island along line PBPD, enhanced tidal mixing eroded the two-layer structure, again cooling the surface and bringing salts (not shown) and nutrients to the surface. Coldest temperatures (<4 °C) on this line occurred in the bottom layer at the boundary between the middle shelf and Pribilof domains, perhaps a result of sea ice that was present northeast of St. Paul Island during April (Stabeno et al., 2008).

At the western side of the transect, cold (<5 °C), saltier (not shown), nitrate-rich water was present near the bottom. This transect did not extend to the shelf-break front as do cross-shelf transects CWCE and GDGA. Once again there was no well-defined two-layer structure west of the island and there was low nitrate concentration in surface water.

The southern-most of the three cross-shelf transects, GDGA, extended from east to west–southwest through St. George Island (Fig. 4, bottom panel). GD was measured over a 10 h period on July 31–August 1, and GA over 7.5 h on August 6, with a notable 5 day lag between halves. The eastern half of the transect occupied a region of confluence of the Pribilof, middle, and outer-shelf domains. The west-southwest portion extended over the outer shelf to the shelf break. Unlike the other two cross-shelf transects (PBPD, CWCE), the eastern reach of this transect was in the outer shelf, hence the layered signature of the outer shelf was present at both the eastern and western ends of the transect (Figs. 2 and 4, bottom panel). Some of the warmest temperatures in the vicinity of the islands were observed on this combined transect (up to 12 °C). As with the northern transect, PBPD, the high nitrate concentrations outcropped at the western end, thus supporting the higher production that historically occurs over the shelf break. This vertical frontal structure dividing the Pribilof domain water from the outer-shelf/slope water was more intense than that observed farther north on CWCE and PBPD, with higher nitrate concentrations at shallower depths.

Deeper water on both ends of transect GDGA had isolated areas of water <4 °C. On the eastern half, bottom salinities associated with this colder water were ~32.4 psu (discussed in Section 3.5), much fresher than water found on the western side (~32.7–33.4 psu). This supports the hypothesis that this eastern tongue of cold water is more closely associated with middle-shelf bottom layer than with an intrusion of slope water. The nitrate data also support this since nitrate associated with <4 °C water on the eastern side was ~20 μM kg^{-1}, while on the western side it was >28 μM kg^{-1}.

In three cross-shelf transects, PBPD, CWCE, and GDGA (Figs. 2, 4 and 5), the Pribilof domain widened to the north. Middle-domain waters to the northeast, and north of St. George had typical stratification, mixed-layer depths with surface temperatures >11 °C, and depleted surface nitrate concentrations. To the west in deeper water, nitrate concentrations consistently increased with depth, and high concentrations outcropped at the shelf front break. Temperature and nitrate distributions were

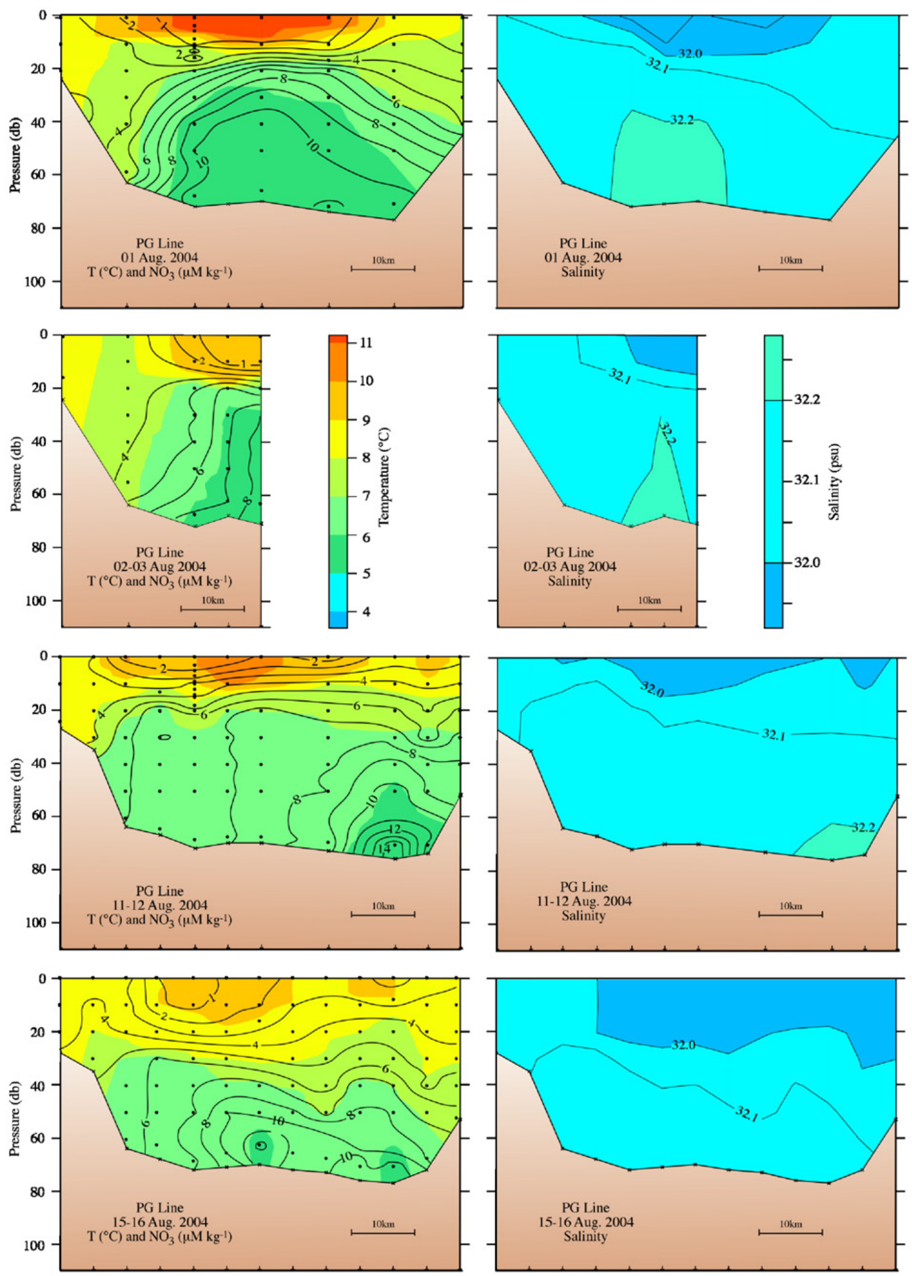

Fig. 6. Contour plots of temperature (color, left), nitrate (lines, left), and salinity (right) on the transect between St. Paul and St. George Islands. Nitrate depths are indicated by dots. North is to the left on each plot. P1 was located east of PG at ~40 km.

similar in the western portion of all three transects. The southern transect contained the sharpest vertical fronts, and the frontal structures became progressively weaker with increasing latitude. Water advected around St. George provided a source of the water along the western side of the islands. The other source was the flow between the islands, which will be discussed next.

3.4. Transects extending between St. Paul and St. George Islands

Four between-island transects (line PG) were occupied: (a) August 1 (6.5 h), (b) August 2–3 (4 h, partial transect), (c) August 11–12 (8.5 h), and (d) August 15–16 (7 h) (Fig. 2). The time progression of the three complete transects (Fig. 6) showed a cooling of the surface waters and an injection of nitrate into the upper layer over this 16-day period. Maximum surface temperatures decreased from 11.8 to 10.6 to 9.4 °C over this time frame, while heat was mixed down into the water column. Mooring data from P1 (Fig. 7) is in agreement, where the time series showed that the mixed layer deepened with increased storminess in mid-July and again in August (Stabeno et al., 2008, and Fig. 7). Changes in temperature were related to the phase of diurnal and semi-diurnal tides and were further modified by fortnightly tide (Kowalik and Stabeno, 1999). Additionally, the water column showed a net freshening, with mean salinity along the transect decreasing from 32.11 to 32.06 psu, and a simultaneous net reduction of nitrate. With the loss of the more saline bottom water, there was a decrease in the vertical gradient. This transformation may be indicative of seasonal change, when wind mixing erodes the two-layer structure as the system transitions to winter conditions.

While enhanced wind mixing is one explanation for the decrease in vertical structure, we must also consider tides as the alternate source of mixing. The tides in this region are semi-diurnal, with reduced stratification associated with the eastwardly flow. An examination of the data from mooring P1 shows that these transects were completed on different parts of the tidal cycle (Fig. 7). On the near-shore, north end of PG lines, note the uniform temperature at 0–5 km and ~25 m depth. The transects extended unusually close to shore, and a well-mixed column temperature is evident in Fig. 6. These observations are consistent with the trapped motion hypothesis of Kowalik and Stabeno (1999).

3.5. Transects around St. George Island

Four transects taken around St. George Island form a progressive clockwise snapshot of water-column characteristics (Fig. 8). GC was measured on July 28–29 over 8.3 h; GB measured July 29–30 over 11.3 h; GD measured July 31–August 1 over 10 h; and GA measured August 6 over 7.5 h. Each transect covered a unique combination of domains. GA, situated north of Pribilof Canyon, encompassed the Pribilof and outer domains, and had a middle-domain influence. Lines GC and GB both crossed lobes of Pribilof Canyon, which has depths >500 m, resulting in the center of GB extending over deep, slope water (>200 m) with both transect ends shoaling on the edges of the canyon. GC extended over the canyon to the slope. GD extended from the Pribilof domain, over the outer shelf toward the shelf break. The combined transect GDGA was discussed in Section 3.3 in the context of cross-shelf comparison of transects (Fig. 4). Adding to that discussion, GA is the most shoreward of the transects at <20 m depth, and 0–2 km distance. The uniformly mixed 7–8 °C water column may indicate trapped motion around St. George (Kowalik and Stabeno, 1999). GB and GC had maximum surface temperatures of >11 °C and bottom average of <5 °C, with a near-bottom cold parcel <4 °C. Additionally, GC was colder over the outer-shelf

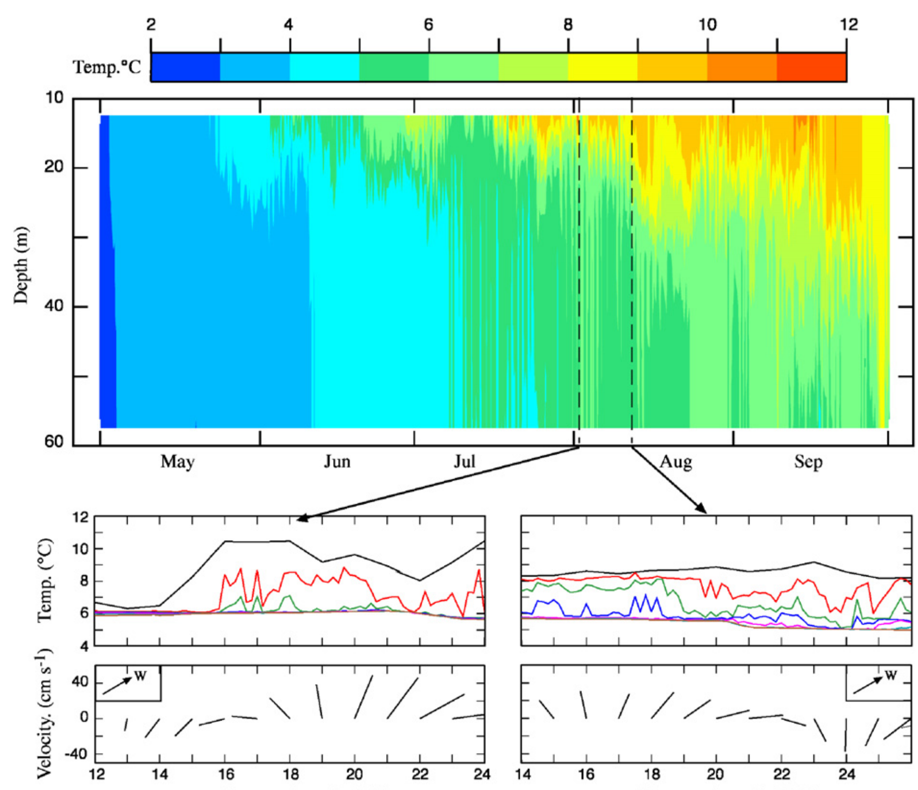

Fig. 7. Mooring P1 water-column temperature time series (above), with plots of current velocity at ~12–14 m, and temperature at five depths (below). Plots show two periods in August coinciding with PG transect occupations. Temperature depths: 12 (black), 21 (red), 41 (green), 51 (blue) and 59 (pink) meters.

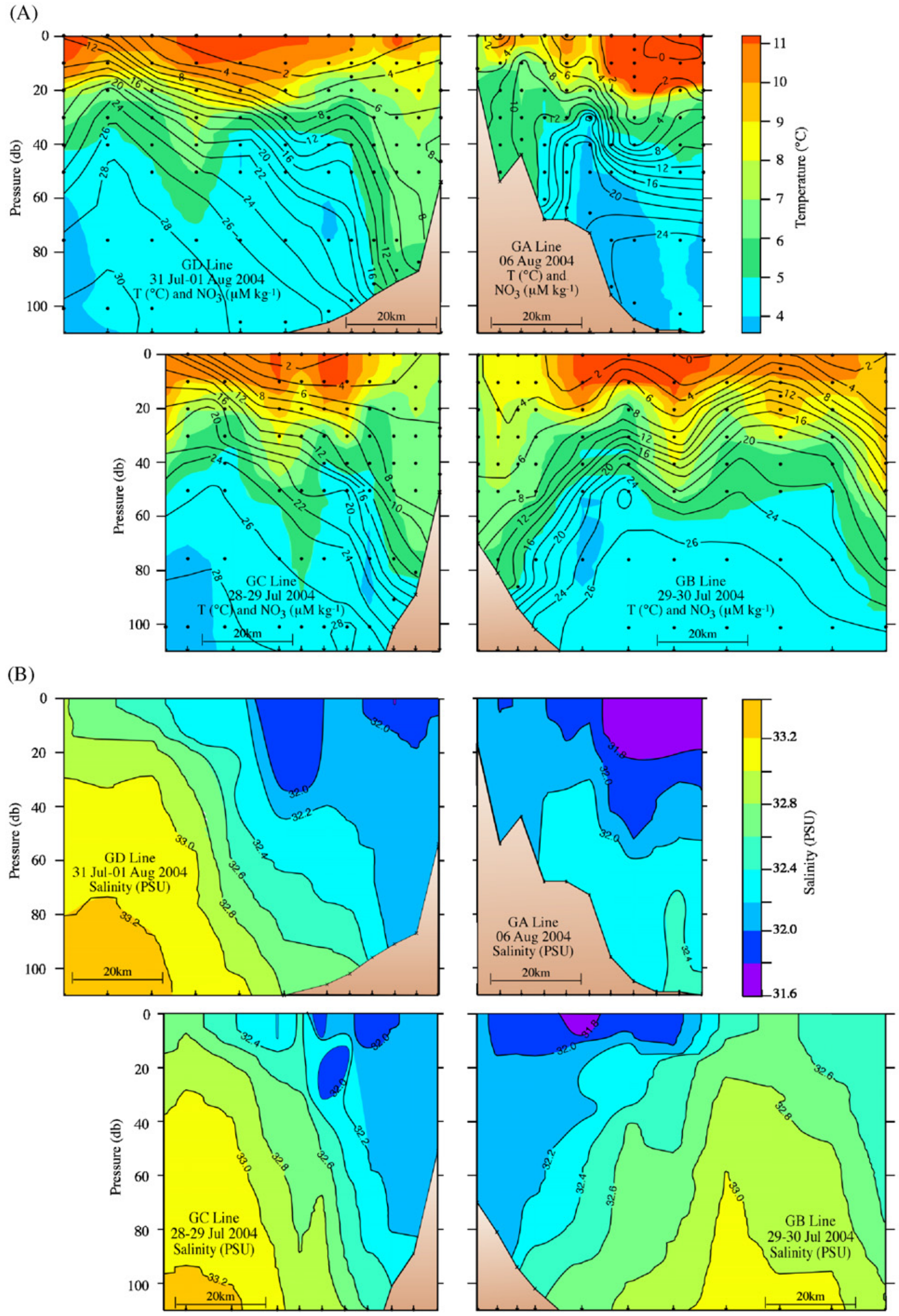

Fig. 8. A: Contours of temperature (color) and nitrate (lines) along four transects around St. George Island. Nutrient sample depths are indicated by dots. Contour plots are arranged relative to position near St. George Island, clockwise from top right, GA, GB, GC, and GD. B: Salinity for the same four transects GA, GB, GC, and GD.

domain. For comparison, summer 1987 and 1988 transects (Coyle and Cooney, 1993), which were similar to GC, showed a smaller temperature gradient both years, with surface temperatures near 10 °C and bottom temperatures near 4.5 °C.

In Fig. 8 we present all four transects, GA, GB, GC and GD, to illustrate patterns and parcels of water progressing around St. George Island. Progressing through each transect, note a cool (<4 °C) filament that appeared at an average 75 m depth (at 25 km on GB). Most extensive on the GA transect, its magnitude decreased as the water flowed around St. George to GB, GC, then GD. This filament was no longer evident on the CW transect north of GD (Fig. 4). Two possible origins of this cold water are: (1) the slope water, or (2) the bottom layer of the middle shelf. Salinity in the cool filament on the GA line was 32.4 psu, slightly more salty than middle shelf bottom water along the CE line (32.2 psu). Salinity remained in the range 32.3–32.5 psu as the filament progressed from GA to GD. The salinity of the 4 °C water at the western reach of the GD transect was 33.3 psu and more indicative of slope water. This suggests that the origin of this filament was mainly middle-shelf water, with some mixing of slope water as it progressed around the island. This is consistent with the results of Mordy et al. (2008) showing a tongue of ammonium-rich middle-shelf water extending over the outer shelf.

Another interesting feature in these transects is the dip in isotherms observed at the center of the GB transect. The effect was slight in GA, at 45 m, and was very pronounced in GB, GC and GD. This feature persisted around St. George Island and north along the 100 m isobath to PB at St. Paul Island (Fig. 4). At GB the 5 °C-isotherm extended to a depth of 60 m, at GC it had deepened to 90 m, at GD it had risen to ~70 m. North of transect GD, the feature shoaled and broke apart. Transect CWCE (Fig. 4, middle panel) shows the feature as it starts to disappear. The northern-most transect PBPD (Fig. 4, top left) shows only the residual shape of this feature in proximity to the frontal structure that separated the Pribilof domain and outer domain waters.

Near-shore salinity at St. George Island remained consistent at 31.8–32.2 psu (Fig. 8B). Clockwise from GA to GD, the outer reach of the transects showed increasing salinity; GA reflected a fresher, layered middle-domain influence, GB showed the more salty shelf-slope bottom at 32.5–33.0 psu, and GC and GD showed increased bottom salinity approaching the vertical structure of the shelf-break front with values >33.2 psu.

3.6. *The combined picture*

Bottom geometry, tides and winds contribute to current patterns around and between the Pribilof Islands, determining the shape of the Pribilof domain, with a narrower region around St. George, expanding to a wider signature north at St. Paul. With accelerated flow and constricted isobaths south–southwest of St. George, currents mixed middle-domain water into the outer-shelf domain and shelf slope, and brought slope water onto the shelf. This is seen in the between-island mixing of the four transects done at PG (Fig. 6), the median westward flow between islands (Fig. 3), flow around the islands (Fig. 3), and middle-domain water movement around St. George Island (Fig. 8A). Nitrate supplied to the surface between islands supported new production in summer. The fronts constrained across-front transfer and promoted along-front water motion and exchange. Mooring P1 near St. George showed a middle-domain pattern of layers, though compared to M2 on the middle shelf, the two-layered system appeared later in summer with less of a temperature gradient between top and bottom layers (Stabeno et al., 2008, Fig. 9). This was likely due to stronger mixing in the Pribilof domain. Bottom-layer nitrate was seen along the eastern extent (middle shelf) of transects in 2004, with concentrations of ~10 μM which are typical for that region in summer (Whitledge et al., 1986, 1988; Kachel et al., 2002). For comparison, in the first noted coccolithophorid bloom in 1997, nutrients in the middle-domain bottom layer were depleted (Stockwell et al., 2001; Kachel et al., 2002). These emerging patterns in this region beg comparison with future years' data collection and observation to better reveal interannual trends.

4. Summary/conclusions

The region around the Pribilof Islands is a transition zone of high productivity where hydrographic domains converge across frontal structures. The Pribilof domain is defined by the transition of surrounding domains into a more shallow, mixed coastal-like area surrounding the Islands. Tidal and wind mixing energy are the dominant physical forcing mechanisms, though the effect of wind is reduced in summer. Although water depth is similar to that of the middle domain, the neighboring, deeper outer-shelf domain and shelf-slope water strongly impact water-column temperature and seasonal transition. Close proximity to Pribilof Canyon to the south, and interaction with the current along the 100 m isobath to the west also define the region. Near each island, the water column is well mixed. Between islands, the water-column structure varies with mixing events and heat input. Frontal structure around St. George Island is closer to the island (Fig. 4, bottom panel); while around St. Paul (Fig. 4, top panel), the transition zone occurs over a wider expanse.

While the eastern side of the Pribilof Islands is bathed in middle-shelf water, the western side consists of a combination of vertically-mixed middle shelf and slope waters. These are separated by a front that outcrops over the shelf break, supplying nutrients to the green belt. Vertical mixing occurs predominantly in the shallow regions between St. Paul and St. George Islands, which also supplies nutrients to the green belt.

The proximity of domains around the Pribilof Islands results in an intensification of the baroclinic mean flow, mixing among domains, strong tidal currents, introduction of slope nutrients onto the shelf, and mechanisms by which bottom nutrients are introduced into the euphotic zone where they sustain new production throughout the summer. Currents along the 100 m isobath continue around each island and the island pair, with a net northwesterly flow as shown by the satellite-tracked drifter data. These characteristics can at times support a rich and varied ecosystem, as indicated in summer bird observations (Kinder et al., 1983). In contrast, strong fronts can also form, limiting the cross-shelf flux of oceanic copepods, a food of birds and fish, as was seen in 1997 with a bird die off, a large coccolithophorid bloom and lack of nutrients in the middle-shelf domain (Stockwell et al., 2001; Kachel et al., 2002).

The 2004 season was distinguished by greater dominance of middle domain over the Pribilof domain, compared to 1997 when outer shelf had more influence. Additional data are necessary to better define the variety and balance of mechanisms at work in and around the Pribilof domain. Longer-term hydrography records across domains are necessary to equate seasonal setup to productivity in this region of complex bathymetry and circulation.

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