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Origins of the subsurface ammonium maximum in the Southeast Bering Sea

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ABSTRACT

In the Bering Sea, it has long been argued that ammonium-rich bottom water from the middle shelf of Bristol Bay is tidally diffused seaward resulting in a mid-depth ammonium tongue over the outer shelf. Weak horizontal mean flows in the region (relative to an especially strong tidal component) support this contention. We examined the distribution of ammonium further north in the vicinity of the Pribilof Islands. On the middle shelf, bottom waters had concentrations of 4–7 μmol kg^{-1}, and over the outer shelf there was a mid-depth ammonium tongue. Optimal multiparameter analysis of hydrographic data suggested that bottom waters from the middle shelf were prevalent across the outer shelf, and could account for this ammonium tongue. Drifter tracks demonstrated that middle shelf water was incorporated into a westward flow along the shelf break south of St. George Island, and mean flows derived from several decades of drifter tracks also show prominent cross-shelf advection in the region. This was consistent with a scalar argument suggesting that, in the vicinity of the Pribilof Islands, the seaward movement of middle shelf water, and loss of nitrogen over the middle shelf, was the result of advection rather than tidally driven lateral diffusion.

1. Introduction

In summer, the middle shelf of the southeast Bering Sea is a well-defined, two-layer system with a wind-mixed surface layer and a tidally mixed bottom layer that are separated by an intense pycnocline (2–5 m thick in the southern portion of the shelf). In the surface layer, ammonium concentrations remain low due to the preferential uptake of this reduced form of nitrogen by phytoplankton (Zehr and Ward, 2002). In the bottom layer, very high ammonium concentrations occur about 1 month after the spring bloom (Whitledge et al., 1986). Ammonium concentrations are some of the highest recorded for unpolluted, well-oxygenated ocean waters, and this is attributed to remineralization of spring production, benthic production (Whitledge et al., 1986), and an extremely long residence time (Coachman, 1986).

Over the outer shelf, Whitledge et al. (1986) observed an intense subsurface ammonium tongue 2–4 weeks after the spring bloom. They argued that the ammonium tongue originated from the middle shelf bottom water moving off the shelf via tidally induced lateral diffusion (Whitledge et al., 1986; Rho et al., 2005). In an early application of the CTD vertical profiler, interleaving layers were observed at mid-depths on the outer shelf, and were thought to result from lateral diffusion of bottom water off the middle shelf (Coachman and Charnell, 1979; Coachman and Walsh, 1981; Coachman, 1986). Lateral diffusion was argued to continue seaward until reaching the northwestward slope flow. The origin of the subsurface ammonium tongue was based on the premise that tidal currents dominated the flow field, and that horizontal gradients of ammonium in the along-shelf direction were small, making the advective flux along the outer shelf of secondary importance.

Beyond the shelf break, a less-intense subsurface ammonium maximum is found across the Bering Sea basin and along Kamchatka Peninsula (Saino et al., 1983; Whitledge et al., 1988). Saino et al. suggested that this maximum was autochthonous (formed at the location observed), and could be explained from postulates found in the model of Jamart et al. (1977), i.e. that the maximum resulted from a combination of turbulent mixing, particle sinking, uptake by phytoplankton, and regeneration by zooplankton. Certainly the shelf is not the source of this maximum, because advection across and around the basin can take >6 months, and winter mixing exceeds 150 m.

Much of the previous work was conducted along the historic PROBES line, a cross-shelf hydrographic line that originates in Bristol Bay, and is located >250 km south of the Pribilof Islands. While monthly mean along-shelf flow at the PROBES line was

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weak (~1–5 cm s^{-1}), that is not the case of the shelf flow south and west of the Pribilof Islands (Stabeno et al., 2008). The notion that the ammonium tongue over the outer shelf results from lateral diffusion must be revisited for this area. In this note, we examine the distribution of ammonium, the seaward extent of middle shelf water, and the relative roles of diffusion and advection in sustaining the subsurface ammonium maximum over the outer shelf in the vicinity of the Pribilof Islands. If not autochthonous, the ammonium tongue represents a loss of nitrogen from the middle shelf. Because ammonium uptake by phytoplankton represents regenerated production (Dugdale and Goering, 1967), and the occurrence of ammonium inhibits nitrate uptake (Dortch, 1990), injection of ammonium into the euphotic zone through diffusion, diapycnal or cross-shelf mechanisms can impact local biogeochemistry.

2. Methods

A hydrographic survey was conducted near the Pribilof Islands on the R/V *Alpha Helix* in July and August 2004 (cruise number HX288, Fig. 1). Ten hydrographic transects extended outward from the Pribilof Islands and crossed the various oceanographic domains found across the shelf. CTD casts were taken with a Seabird SBE-911 Plus system. Salinity calibration samples were taken on all casts and analyzed on a laboratory salinometer.

Water from all the hydrocasts were analyzed for ammonium. Samples were collected using 5-L Niskin bottles attached to the CTD rosette, and subsampled for ammonium using 50 mL high-density polyethylene bottles that were soaked 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. Ammonium was analyzed using a Technicon II Auto-analyzer. Standardization and analysis procedures specified by Gordon et al. (1993) were closely followed including calibration of labware, preparation of primary and secondary standards, and corrections for blanks and refractive index.

Satellite-tracked drifters have been deployed for two decades in the region with over 500 satellite-tracked drifters (each drogued at 40 m with a holey sock) deployed in the Bering Sea and Gulf of Alaska. Approximately half of these have transited the eastern Bering Sea producing a rich data set of Lagrangian flows. During summer 2004, 20 satellite-tracked drifters were deployed onto the eastern shelf with approximately 15 fixes obtained each day.

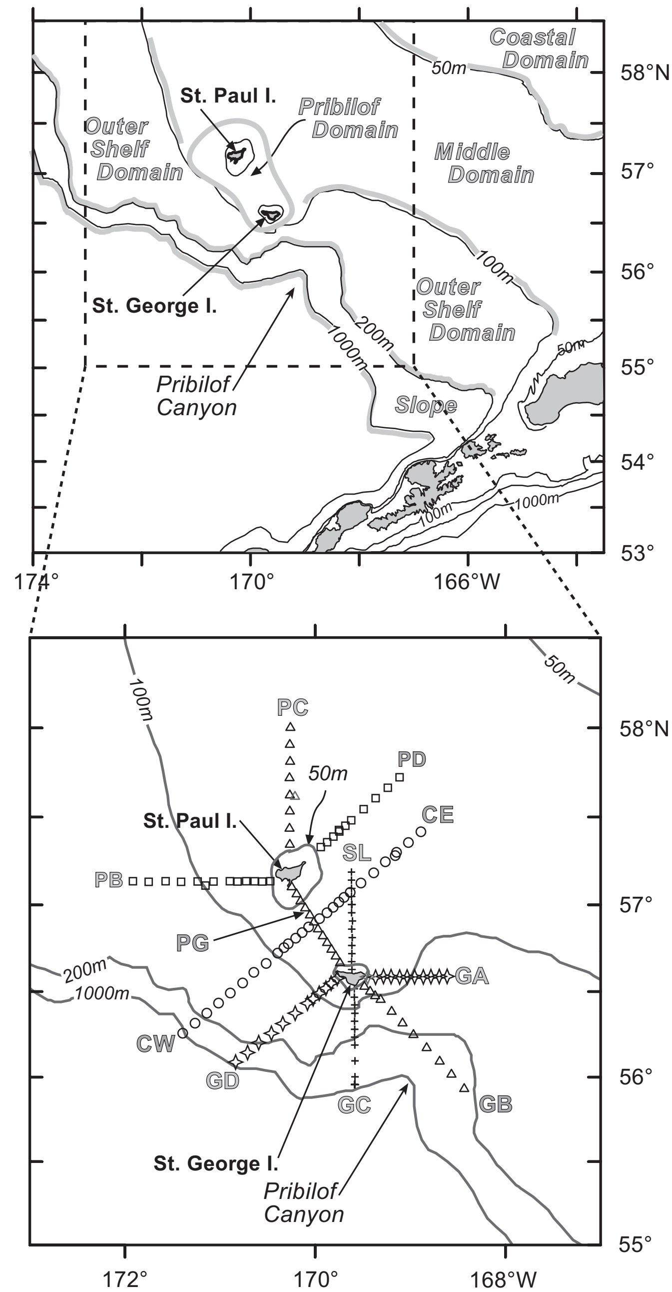

Fig. 1. Map of the study area with identification of domains (top), and the name and location of the hydrographic transects during cruise HX288 (bottom). Transects with identical symbols were combined to produce the cross-shelf sections shown in Figs. 2 and 4.

3. Results

3.1. Distribution of ammonium

Ammonium was sampled over the three distinct hydrographic regimes discussed by Sullivan et al. (2008): the Middle Domain, the Outer Domain, and the Pribilof Domain (Fig. 2). The Middle Domain (typical water depths of 50–100 m) was sampled at the northern end of the PC, PD, CE, and SL lines. It was a two-layer system with an upper wind-mixed layer, a strong (2–5 m) pycnocline, and a tidally mixed bottom layer. Ammonium concentrations were typically $<0.5\,\mu mol\,kg^{-1}$ in the upper layer, and between 4 and $7\,\mu mol\,kg^{-1}$ in the bottom layer. The Pribilof Domain was sampled on all lines, was tidally mixed with a very weak pycnocline, and had surface ammonium concentrations that varied between 0.5 and $5.5\,\mu mol\,kg^{-1}$. The outer shelf (100–180 m) was sampled on the GA, GB, GC, GD, PB, and CW lines, with the GC, GD, and CW lines extending to the shelf break, and the GC and GB lines extending into Pribilof Canyon. The outer shelf was a three-layer system having a less intense pycnocline, a middle layer with extensive temperature fine-structure (in a region of strong cross-shelf flow), and a bottom layer comprised of slope water and water flowing along the 100-m isobath (Sullivan et al., 2008). Ammonium concentrations in the outer shelf were typically $<1\,\mu mol\,kg^{-1}$ in the surface layer and $<0.2\,\mu mol\,kg^{-1}$ in the bottom layer. In the middle layer, there was a tongue of ammonium that shoaled seaward and was less intense over the deeper water.

3.2. Optimal multiparameter analysis

To determine the likelihood that the tongue of ammonium found over the outer shelf was derived from middle-shelf bottom

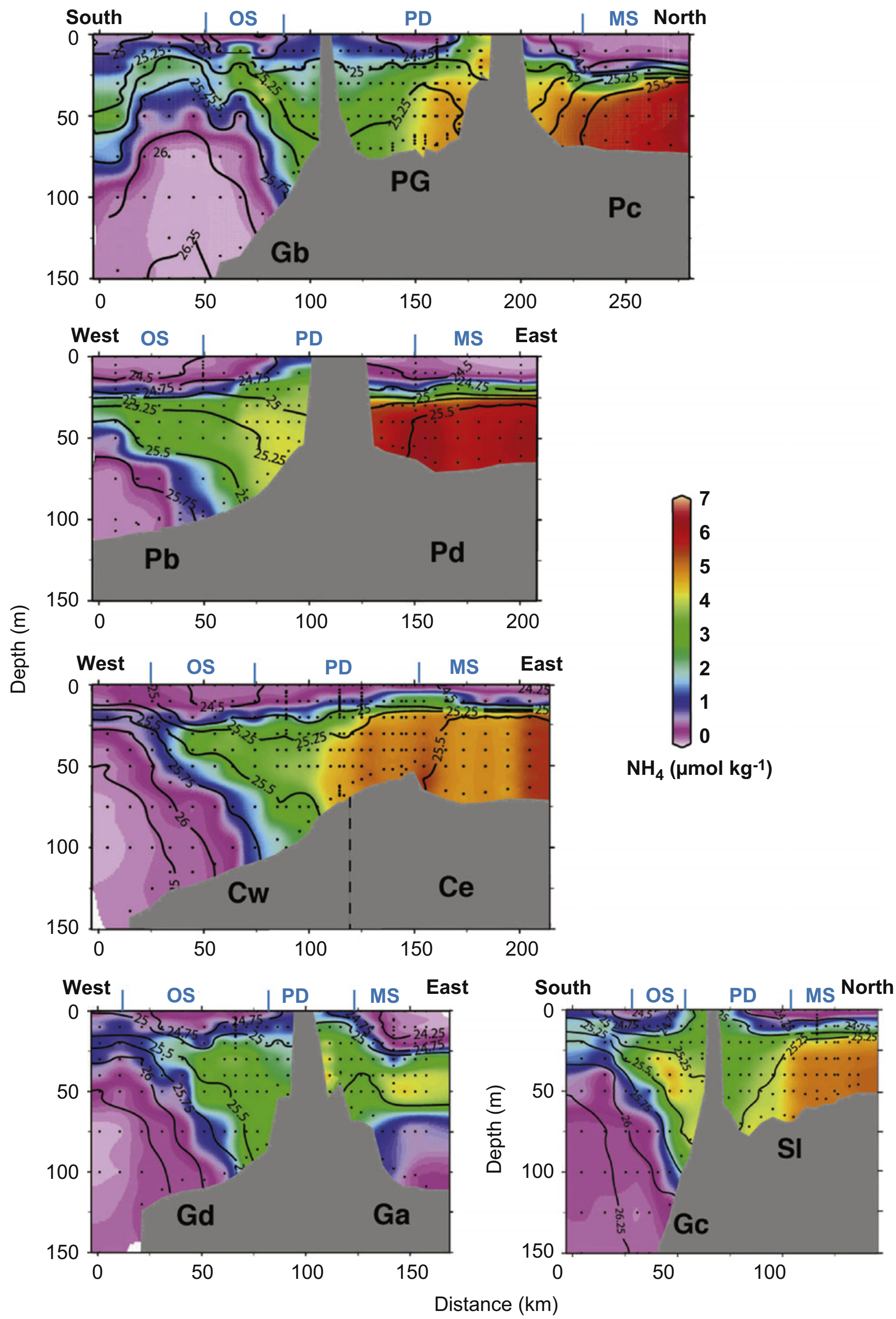

Fig. 2. Vertical sections of ammonium (color, $\mu mol\ kg^{-1}$) overlaid with contours of potential density. Shelf domains (MS = Middle Shelf, PD = Pribilof Domain, OS = Outer Shelf) are indicated at the top of each section. A subsurface ammonium tongue is observed over the outer shelf in each section. (For interpretation of color, please see the figure in online version).

water, we estimated the mixing fractions of water masses over the shelf using optimal multiparameter (OMP) analysis (Tomczak, 1999; Poole and Tomczak, 1999). OMP estimates the contribution of pre-determined water types for each data point by inverting a linear set of mixing equations. Five water types were identified in the study area: middle-shelf upper water (MSUW), middle-shelf bottom water (MSBW), outer-shelf upper water (OSUW), outer-shelf bottom water (OSBW), and water flowing northward along the 100-m isobath (IB, Sullivan et al., 2008). Water types were identified in T-S space (MSBW, OSBW) or phosphate-S space (MSUW, OSUW, IB) (Fig. 3). Surface water types were identified in phosphate-S space, because surface temperatures were too variable to reliably identify these water types in T-S space. The parameters incorporated into the OMP analysis for characterizing each water type were potential temperature, salinity, nitrate, phosphate, and silicic acid (oxygen was not measured). Nutrient data were regarded as quasi-conservative, and this assumption was based on the relatively small study area, post-bloom conditions, and the use of local data for characterizing the water types.

OMP analysis was conducted using equal weighting functions for each of the parameters. There were instances where MSBW

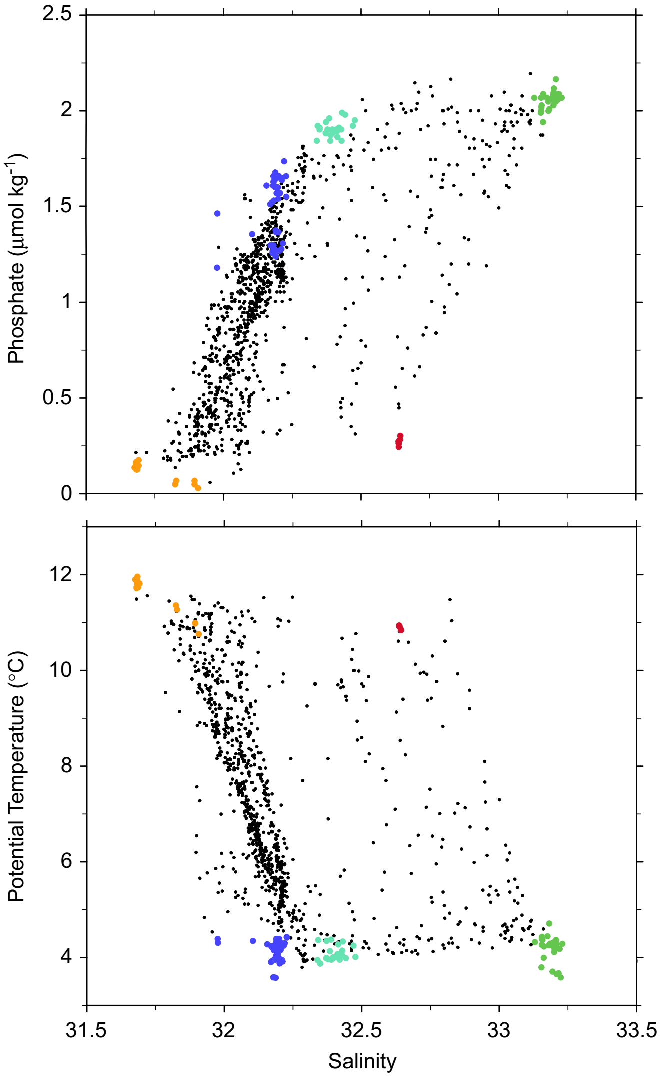

Fig. 3. Phosphate (top) and potential temperature (bottom) vs. salinity with colors indicating the different water types: MSBW (blue), IB (aqua), OSBW (green), MSUW (orange), and OSUW (red). (For interpretation of color, please see the figure in online version).

was assigned to the well-stratified surface waters of the middle shelf; a peculiarity stemming from variable surface temperatures. An average surface temperature of 11.6 °C was used to define MSUW. As a result, surface samples warmer than 11.6 °C were assigned values of $>100\%$ MSUW, and in these cases the result was set to 100%. Conversely, surface samples cooler than 11.6 °C were assigned a portion of MSBW, an unrealistic result for the well-stratified water of the middle shelf. (Due to tidal mixing, MSBW contributed to surface waters around the Pribilof Islands and over a shoal located near the intersection of the CE and SL lines.)

Results of the OMP model were used to create vertical sections of the %MSBW around the Pribilof Islands (Fig. 4). Note the large contribution of MSBW to surface water, where tidal mixing breaks down the thermocline (the Pribilof Domain and the shoal on the CE and SL lines), and at the southern end of the GB line. The GB line crossed over the Pribilof Canyon and the outer shelf, and approached the opposite bank of the Pribilof Canyon. The contribution of MSBW along the GB line were lowest (~0–10%) over the deepest portions of the line. But at the southern end of the section, surface waters were cooler and fresher; hence, the model result included a fraction of MSBW at the surface, highlighting the problem discussed above. North of St. Paul, the PC line extended well into the middle shelf, and the model found that the bottom layer was typically 50–60% MSBW, with a large fraction of IB water. This was consistent with the findings of Stabeno et al. (2008) that the middle shelf north of St. Paul was not isolated from the shelf break, but was a region of on-shelf flow. Also, this transect was unique in that it crossed into a portion of the middle shelf that had been ice covered in spring, and had experienced a significant ice-edge bloom. High ammonium concentrations along this line may be a product of this bloom as ice-edge blooms in the Bering Sea often sink to the bottom.

The primary feature in these sections was a tongue of MSBW over the outer shelf. The PB line did not extend to the shelf break and in this section, the MSBW tongue fully encompassed the subsurface ammonium maximum. The GC, GD, and CW lines continued to the shelf break, and in these sections the MSBW tongue faded at the shelf break such that only a few scattered data points seaward of the break had appreciable MSBW.

Taken together, these model results suggest that the ammonium tongue on the outer shelf could have been derived from MSBW, but the subsurface ammonium maximum extending beyond the shelf break was not.

4. Discussion

4.1. *The Bering Sea shelf*

The southeastern Bering Sea has a broad and shallow shelf that can be separated into three oceanic regimes, the tidally mixed inner shelf (<50 m, not discussed here), the middle shelf and the outer shelf (Coachman, 1986; Sullivan et al., 2008). The middle shelf is located approximately between the 50 and 100-m isobaths; and, in summer, the monthly mean flow is very weak ($<1\,\mathrm{cm\,s^{-1}}$ in summer, Stabeno et al., 2007). The two-layer structure begins to set up in April concomitant with increasing solar radiation and decreasing winds. By late spring, nutrients in the upper layer have been stripped away due to spring production (Whitledge et al., 1986; Rho et al., 2005), and the chlorophyll maximum is found near the pycnocline, where there is sufficient light and nutrient supply via vertical diffusion and diapycnal mixing. By midsummer, the bottom layer has extremely high ammonium concentrations (4–8 μmol kg^{-1} in this study) due to remineralization of spring production and benthic production (Whitledge et al., 1986).

Separating the middle shelf from the outer shelf is the middle front. The middle front follows the 90–100-m isobaths to the northwest, and its location is essentially the depth at which isopycnals from the slope flow (that deepen shoreward) encounter the bottom (Coachman, 1986). The outer shelf is a three-layer system with a wind-mixed surface layer and a tidally mixed bottom layer separated by a middle layer with fine-structure.

4.2. *The ammonium tongue over the outer shelf*

Typical subsurface ammonium maxima in the ocean are weak ($<1\,\mu$M) and confined to the base of the euphotic zone (as observed at the seaward end of the GC and GD lines). Such maxima stem from autochthonous biological and physical processes, e.g. rapid uptake of ammonium by phytoplankton in the upper mixed layer, and, below the euphotic zone, an imbalance between the remineralization of particulate nitrogen and vertical mixing across the pycnocline (Brzezinski, 1988).

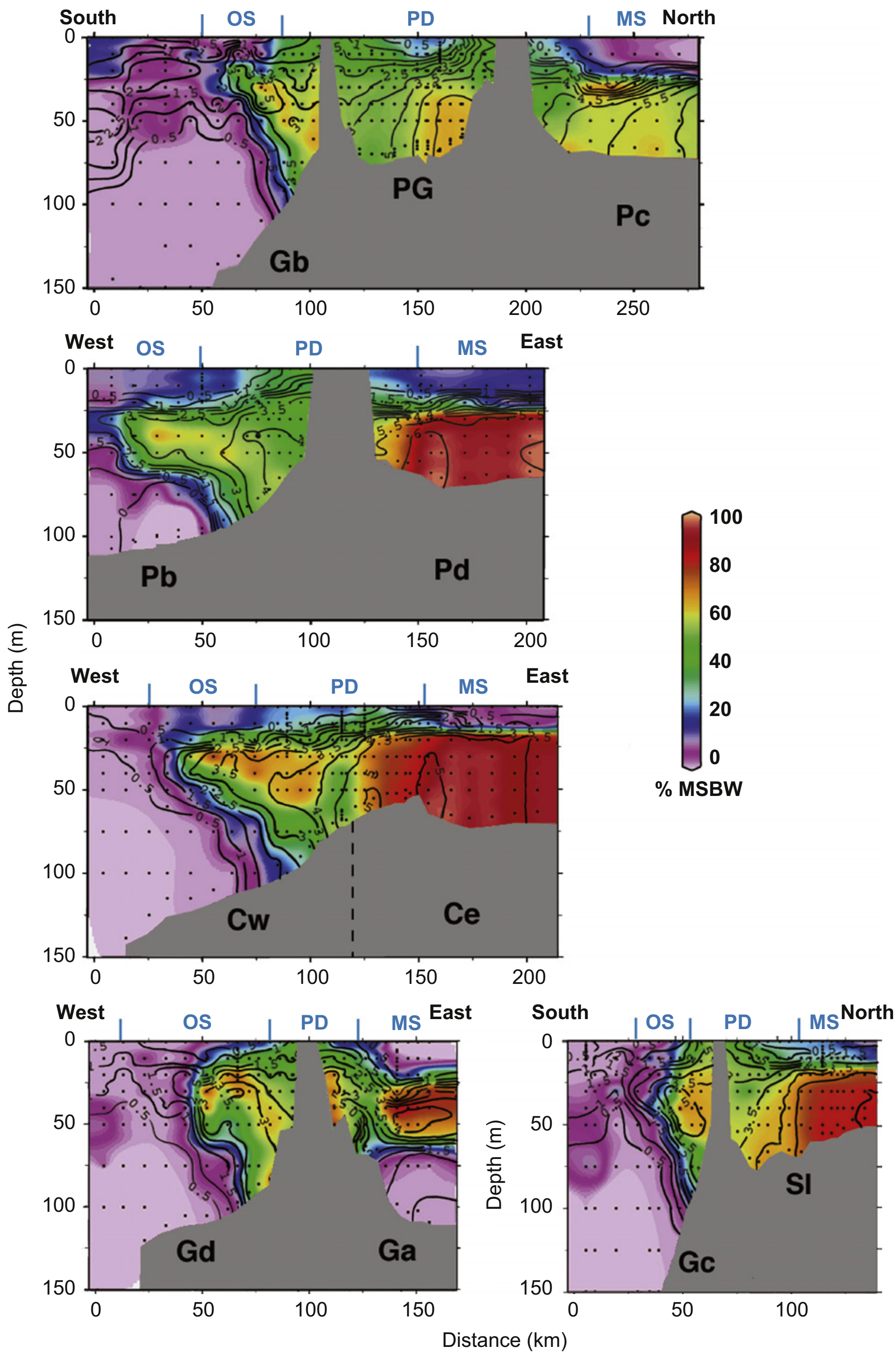

Fig. 4. Vertical sections of the %MSBW (color) overlaid with contours of ammonium (μmol kg^{-1}). Shelf domains are indicated as in Fig. 2. (For interpretation of color, please see the figure in online version).

On the Bering Sea shelf, we found very high ammonium concentrations, and our results were consistent with previous observations in the Bering Sea. High concentrations were observed in MSBW, a tongue of high ammonium was observed over the outer shelf, and a weak subsurface maximum of ammonium was observed beyond the shelf break (Fig. 2). Our results demonstrate the persistence of these features both spatially and decadally.

Satellite imagery of chlorophyll-*a* distributions show highly variable concentrations in the region during spring and early summer, and especially high concentrations near the slope flow or "green belt". However, ammonium concentrations decreased near the shelf break, and were relatively low under the photic zone of the green belt. The thickness and intensity of the ammonium tongue over the outer shelf suggested an additional "outside" source of ammonium. It has been hypothesized that the ammonium tongue originated from intrusions of MSBW over the outer shelf (Whitledge et al., 1986; Rho et al., 2005). Using a two-endmember mixing model, Coachman (1986) estimated the proportion of MSBW in outer Bristol Bay (along the PROBES line, see his Fig. 45). He identified a tongue of MSBW over the outer shelf of the PROBES line that shoaled and faded seaward. West of the Pribilof Islands, moored instrumentation also revealed the presence of MSBW in the upper 50 m over the outer shelf (Stabeno et al., 2008). OMP analysis on the hydrographic data identified mixing proportions of different water types. A tongue of MSBW was found over the outer shelf, and was generally coincident with ammonium distributions. Compared to the more southerly results of Coachman, the core of this tongue was ~20 m shallower and had a higher proportion of MSBW (e.g., 10–15% higher at the 100-m isobath).

4.3. Advection– diffusion

Along the PROBES line, the presence of MSBW over the outer shelf was argued to result from tidally driven lateral diffusion, because mean flows along the outer shelf were found to be insignificant (Coachman and Charnell, 1979; Coachman and Walsh, 1981; Coachman, 1986). However, in the vicinity of the Pribilof Islands, along-shelf and cross-shelf advection were significant especially on event scales of 1–3 days (Stabeno et al., 2008) and appear to be a significant mechanism for moving ammonium-rich MSBW over the outer shelf.

The flow field around the Pribilof Island was determined from a combination of drifters and moored current meters. Satellite-tracked drifters were used to generate a Lagrangian map of the mean flow (Fig. 5, Stabeno et al., 2008) that revealed the anticyclonic circulation around the islands, a well-defined Bering Slope Current at the shelf break, and generally weak flow over the middle shelf that occurred to the east of the islands. Over the shelf, the strongest low-frequency flows were on the narrow shelf to the south of St. George Island where currents exceeded $20\,cm\,s^{-1}$. Along the outer shelf west of the Pribilof Islands, the strongest Lagrangian flow was to the northwest and seaward of the 100-m isobath. Currents measured at the mooring sites showed the same general pattern, although the mean Eulerian flows were weaker than the Lagrangian flows. These flows were not insignificant.

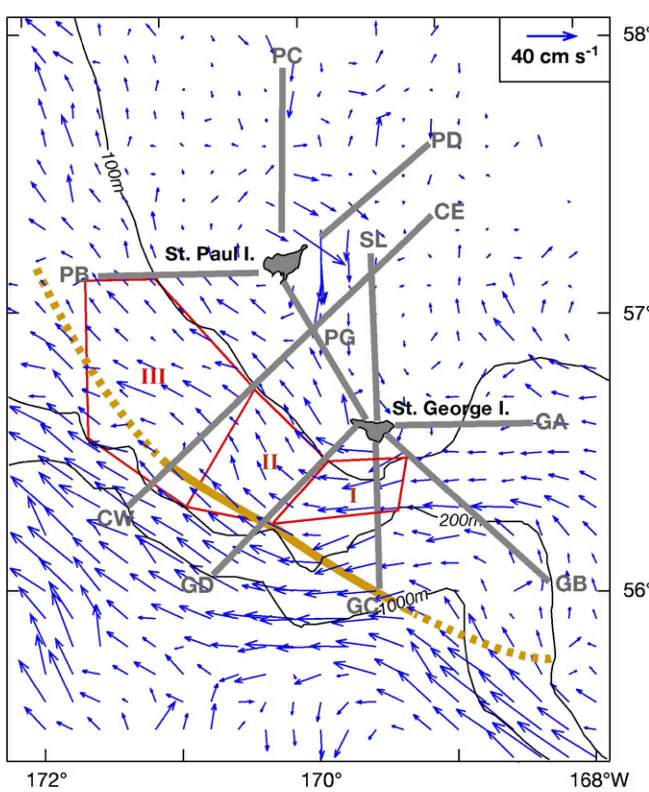

Fig. 5. Composite (1985–2005) of Lagrangian currents at ~40 m using satellite-tracked drifter trajectories (from Stabeno et al., 2008). The gray lines indicate the location of hydrographic transects; the orange line denotes the seaward extent of the subsurface ammonium tongue ($>1.5\,\mu mol\,kg^{-1}$); and the red bins show the regions in which average flow was calculated along the outer shelf in Table 1. (For interpretation of color, please see the figure in online version).

Flow over much of the rest of the southeastern shelf was much weaker. For instance, mean flows over the middle shelf are $<1\,cm\,s^{-1}$. The flows in the vicinity of the Pribilof Islands were stronger than the $\sim 5\,cm\,s^{-1}$ flow reported over the outer shelf of Bristol Bay (Coachman and Charnell, 1979; Coachman, 1986). Even over this portion of the outer shelf, there were short-term events (days) where on shelf flow exceeded $20\,cm\,s^{-1}$ (Stabeno and Van Meurs, 1999). In addition, the along-shelf Lagrangian velocities can exceed $30\,cm\,s^{-1}$ for period of weeks (Stabeno et al., 2008). This is comparable to tidal currents.

In the narrow gap between St. George Island and Pribilof Canyon, the constriction of isobaths and a westward turn in bathymetry resulted in a strong and persistent westward Lagrangian current with speeds $>30\,cm\,s^{-1}$ (Stabeno et al., 2008). Drifters flowing to the northwest along the shelf break were repeatedly entrained in this current, as were drifters to the east of the Pribilofs that were over the middle shelf. (Note that, due to a lobe in Pribilof Canyon, some regions east of the Pribilofs are not in the middle shelf.) For example, during the summer of 2004, three drifters were oriented across the middle shelf to the east of the Pribilof Islands (Fig. 6). Because the drifters were drogued at 40 m, they tracked the movement of MSBW. The drifter furthest inshore (north) appeared to move in a random walk, and was not influenced by offshore flow south of St. George. The other two drifters migrated to the southwest, and were sequentially entrained and advected in the 100-m isobath flow. Drifters from other years that were located in the same vicinity on the middle shelf (to the southeast of St. Paul) were frequently entrained in this westward flowing current, as were drifters that were being advected along the shelf break. Hence, ammonium-rich waters along the GB and GC lines represented the confluence and seaward advection of middle shelf water originating east–northeast of the Pribilof Islands and water from the shelf break including ammonium-rich middle shelf water that had diffused over the outer shelf to the south.

This reasoning is consistent with a scale argument used to examine the relative importance of advection and diffusion. The transport of a tracer can be represented by the Peclet number, $Pe = uL/\kappa$. Here u and L are the velocity and length scales of the system being studied and κ is the eddy diffusion coefficient. The higher the Peclet number, the more important advection is for the transport of a tracer compared to diffusion. Using a conservative cross-shelf scales of 0.1 m/s (based on 20 yr of Lagrangian measurements) and 50 km for u and L, and an estimate of κ that encompasses most oceanographic observations (1×10^2 to $1\times10^3\,m^2\,s^{-1}$, Coachman, 1986), the Peclet number is 5–50. This suggests that advection should dominate for this system.

To examine the likelihood that the ammonium tongue was autochthonous, we averaged the Lagrangian flow field over the outer shelf in three bins as shown in Fig. 5 (Table 1). On average, these results suggest that water flows around the Pribilof Islands in about 3 weeks. Data from Whitledge et al. (1986) suggest that the ammonium pool in spring over the middle shelf develops 2–4 weeks after the spring bloom. If similar remineralization rates hold for the outer shelf in summer, then the flow seaward of the Pribilof Islands is great enough to preclude an autochthonous origin of the ammonium tongue in each of these bins.

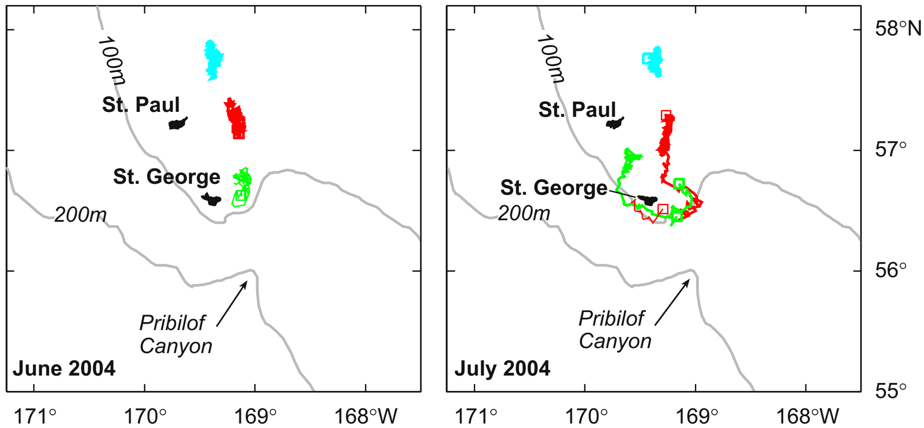

Fig. 6. Monthly trajectories of three satellite-tracked drifters that were in the vicinity of the Pribilof Islands in June (left) and July (right), 2004. Squares indicate the position of each drifter at the beginning of the month.

Table 1
Average Lagrangian velocities and residence times for a water parcel in each of the bins denoted in Fig. 5

Bin	Approximate distance (km)	Velocity ($cm\,s^{-1}$)		Approximate residence time (d)
		x	y	
I	45	−12.4	−1.3	4
II	40	−5.3	6.4	6
III	60	−6.1	4.5	11

Distances and residence times were estimated by following two track lines through the bins.

5. Summary

Around the Pribilof Islands, bottom water from the middle shelf is incorporated into an intense off-shore flow south of St. George Island, resulting in fresher, colder, and ammonium-rich water being advected over the outer shelf, representing the loss of nitrogen over the middle shelf in this region. While the intense ammonium tongue over the outer shelf is largely derived from middle-shelf water, middle-shelf water is not present beyond the break. Hence, the weak subsurface ammonium maximum seaward of the break is most likely of autochthonous origin.

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