AYK Sustainable Salmon Initiative

2011 Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative Project Final Product[1]

JUVENILE SALMON DISPERSAL: A DRIFTER VIEW

by

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I. ABSTRACT:

The project involved the deployment, tracking, and analyses of satellite-tracked drifters between June and October in Kuskokwim Bay between June and October in both 2008 and 2009. The project's goal was to examine nearshore circulation pathways which may be used by outmigrating juvenile salmon from the Kuskokwim River. In each year 32 drifters were deployed by the residents, including schoolchildren, of Quinhagak. Drifter trajectories were updated daily and placed on the project webpage (http://www.ims.uaf.edu/NPRBdrifters/). We find that the circulation varies spatially and seasonally. In summer many of the drifters move westward in a coastal flow from the bay and thence northwestward toward Etolin Strait. Other drifters move southward along the main channel of the bay and some are captured in an eddy north of Cape Newenham. By late August, winds intensify and the drifters move offshore and onto the central Bering shelf. These flow patterns were seen on both years. Our results suggest that if salmon are moving westward in the nearshore flow in summer, that feeding here may be poor since the region is engulfed by nutrient-poor, low-salinity waters that are probably biologically unproductive. In contrast, salmon moving southward through the Bay or offshore in late summer are likely to encounter better feeding conditions. We have established simple statistical relationships between offshore drifter displacement and winds that allow characterization of the shelf surface flow field and we have defined the dominant Lagrangian space and time scales of the circulation.

Keywords: Bering Sea nearshore circulation, salmon habitat, satellite-tracked drifters

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III. INTRODUCTION:

Chinook and chum salmon returns to the Kuskokwim and Yukon rivers and Norton Sound drainages have shown remarkable interannual variability in the recent past. Although the causes underlying these returns are not understood, the variations in recruitment success are regional in scale, suggesting that conditions in the marine environment are the culprit. Indeed, marine survival of salmon appears to depend critically upon ocean conditions, especially during the first few months that the young fish spend in the ocean after leaving their freshwater rearing habitats [*Beamish and Mahnken*, 2001]. While a variety of ocean-related phenomena can affect salmon survival during their early marine life stage, nearshore currents may be are critically involved in the transport and dispersal of juveniles and/or their prey. Restoration and conservation strategies for Bering Sea salmon stocks requires understanding the migratory routes and the shelf habitats salmon use during their early marine life.

This project focused on understanding the circulation structure of the nearshore Bering Sea; the first oceanic habitat encountered by salmon leaving the rivers of western Alaska. Our goal was to provide a first order description of the nearshore circulation in the Bering Sea during the late spring through fall period, when young salmon are entering and maturing on the Bering shelf. Our results suggest the likely oceanic pathways by which salmon enter the various Bering Sea shelf oceanographic domains.

Coachman [1986] and *Stabeno et al.* [1999], and references therein, provide a thorough overview of the physical oceanographic characteristics of the Bering Sea shelf. This enormous shelf extends nearly 500 km westward from the coast to the shelfbreak (~200 m isobath) and ~1000 km northward from the Alaska Peninsula to Bering Strait (**Figure 1**). Although bottom depths increase smoothly from the coast offshore, the bathymetry nonetheless divides the shelf into three distinct biophysical domains (the shelfbreak or outer domain, the middle shelf or central domain, and the inner shelf or coastal domain). Each domain is separated from the other by a frontal system coincident with a particular isobath. Thus, the outer domain extends from the 100 meter isobath to the shelfbreak, the mid-domain lies between the 50 and 100 meter isobaths, and the coastal domain extends from the coast to the 50 meter isobath. Historical efforts concentrated on the region seaward of the 50 meter isobath in the southeast Bering Sea; the major commercial fishing grounds for pollock and shellfish. There is a dearth of information on the circulation field of the inner shelf and this program represents the first comprehensive effort to redress this situation.

The mean flow over the Bering Sea shelf is northward (and parallel to the isobaths) nearly everywhere, and thereby connects the southern Bering Sea shelf to the Bering Strait (**Figure 2**). There are, however, substantial cross-shelf differences in the mean currents with the largest flow over the shelfbreak (10 cm s^{-1}), the weakest (~1 cm s^{-1}) in the central domain, while more modest flows (3 cm s^{-1}) occur in the coastal domain [*Kinder and Schumacher*, 1981]. The mean flow is weak, however, in comparison to both tidal and wind-forced subtidal currents (subtidal currents vary on time scales longer than one day), which can be as large as ~50 cm s^{-1} and persist for several days. Although tidal current magnitudes vary spatially, the tides comprise a major fraction of the total kinetic energy budget of the shelf [*Coachman,* 1986; *Schumacher and Kinder,* 1983] and are an important agent for vertical mixing.

Water mass properties also vary across the shelf, with these differences dependent upon water depth and the relative importance that advective and diffusive processes play in structuring the water column. Vertical mixing, in particular, plays a significant role in this regard, with the mixing energy derived primarily from the wind in the surface layer and through tidal friction within the bottom boundary layer. Shelfbreak waters are moderately stratified and their properties are set by lateral exchanges, induced by tides, slope eddies, and wind-forced currents, between the basin and the central shelf. From late spring through fall the central domain waters include a strong pycnocline (a depth layer across which seawater density increases rapidly) at mid-depth that separates a homogeneous, wind-mixed surface layer, from a tidally mixed, bottom boundary layer. Bottom water properties are largely established during the previous winter [*Stabeno et al*., 1998] while surface layer properties depend upon ice melt, the annual cycle of solar heating, and exchanges with relatively fresh coastal domain waters.

The coastal domain, which varies in width from 20 – 100 km, extends northeastward along the Alaska Peninsula beginning at Unimak Pass, includes the inner portion of Bristol Bay, and continues northward to Norton Sound and Bering Strait. The region is a potential pathway by which waters from the Gulf of Alaska shelf are transported into the nearshore Bering Sea [*Stabeno et al*., 1999; *Royer*, 1999] and eventually northward through Bering Strait [*Coachman*, 1986]. Nearshore currents vary in response to tides, winds, and freshwater runoff with this response changing from spring through fall due to variations in river discharge and winds.

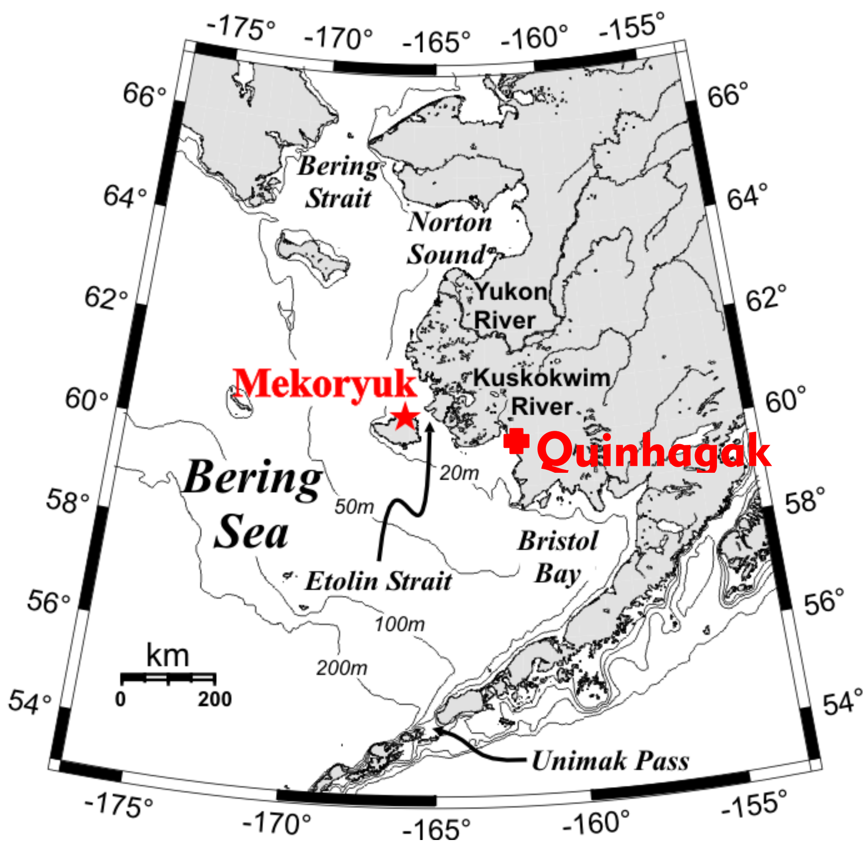

Figure 1. The eastern Bering Sea shelf. Drifter deployments were based from Quinhagak south of the mouth of the Kuskokwim River.

Within the coastal domain the bottom boundary layer merges with the surface mixed layer to produce a vertically homogeneous water column. However, seawater density decreases shoreward [*Straty*, 1977; *Myers*, 1976; *Kachel et al.*, 2002] implying that a northward (along-shore) flow tendency is established to balance this cross-shore pressure gradient. Coastal domain waters reflect the effects of ice production and melt, solar heating, and the strong seasonal cycle in freshwater discharge from the rivers draining western Alaska.

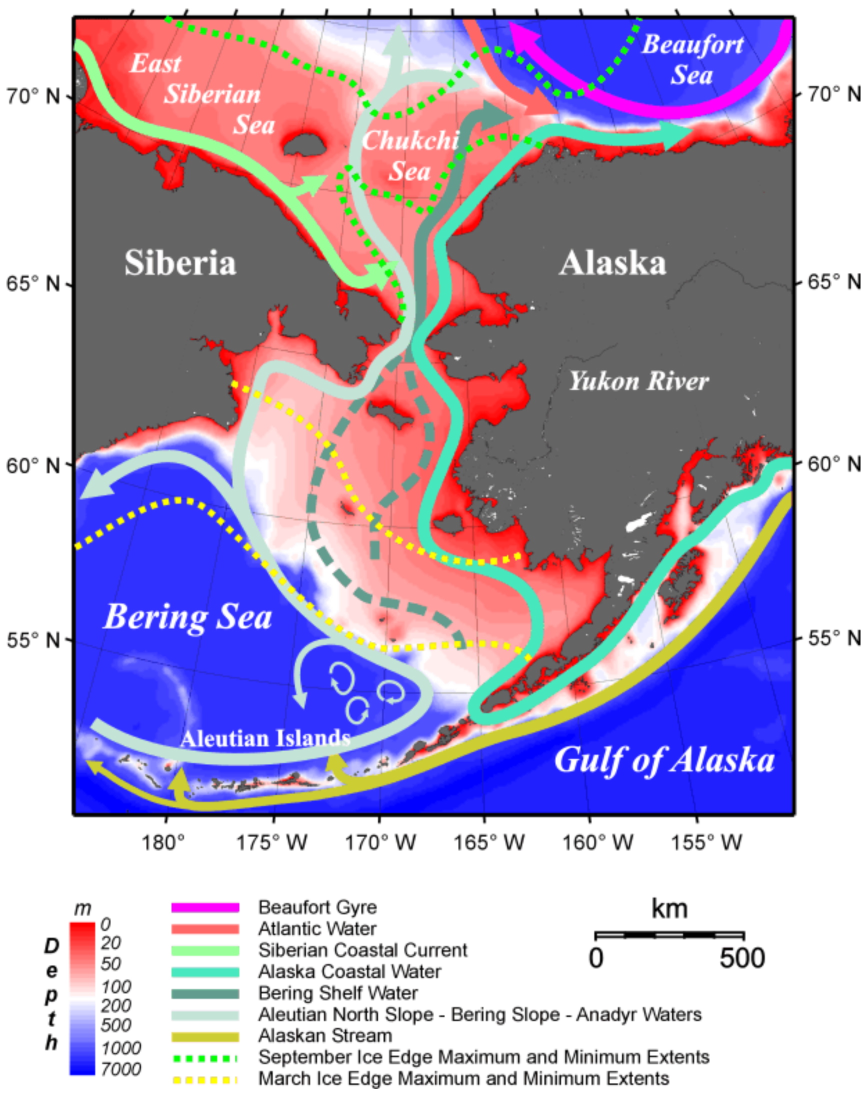

Figure 2. Schematic of the circulation field and water masses of the Bering-Chukchi seas superimposed on the bathymetry.

The focal area of this study is the innermost (nearshore) portion of the coastal domain shoreward of the 20 meter isobath. This broad region, which in some places extends ~100 km from the coast (**Figure 1**), is likely an important transition zone wherein shelf waters mix with the seasonally large coastal freshwater discharge that enters through the numerous rivers draining western Alaska. River discharge increases abruptly in May and attains a maximum in June before decreasing through fall (**Figure 3**). The runoff might establish substantial nearshore vertical and horizontal salinity gradients (fronts) that locally affect mixing, water column properties, and the circulation. For these reasons the nearshore flow field might differ significantly from that observed nearer to the 50 meter isobath. For example, in spite of strong tidal and wind mixing, *Muench et al.* [1981] show strongly stratified conditions in summer and fall in Norton Sound because of the Yukon River discharge. Moreover, theory suggests that low-salinity plumes formed by river outflows should extend from 10 – 30 km offshore, given the typical summer discharge rates for the larger rivers in western Alaska [*Yankofsky and Chapman*, 1997 and *Lentz and Helferich*, 2002].

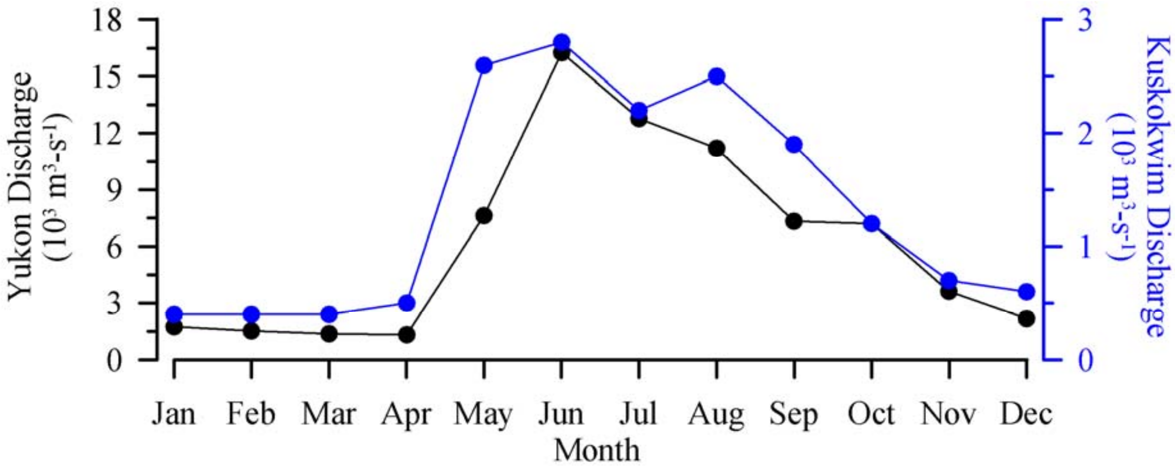

Figure 3. Mean monthly Yukon (black) and Kuskokwim (blue) river discharges. Note scale change between the Kuskokwim and Yukon rivers.

At the outset of this project we believed that the flow from Kuskokwim Bay would move northwestward along the coast eventually passing through Etolin Strait or around the south coast of Nunivak Island. This belief is consistent with theoretical notions and was also suggested by juvenile salmon distributions determined by the BASIS program. For example, the highest concentrations of juvenile chum salmon in 2005 (**Figure 4)** are found to the northwest of Bristol and Kuskokwim bays and west and north of Nunivak Island. Similar distributions occur for chinook, pink, and coho in this and other years (additional salmon species distribution maps and maps from other years are at: http://www.afsc.noaa.gov/abl/occ/basis.htm). (Juvenile sockeye diverge from this distribution pattern. We suspect that this is because these fish are large upon entry into the sea and therefore capable of swimming offshore and onto the southeast shelf where they feed on zooplankton [*C. Stark*, pers. comm..]. The smaller pink and chum juveniles may be advected northward along the coast by the mean flow, while the larger coho and chinook may follow these smaller juveniles and feed upon them.) In aggregate, the maps suggest considerable interannual variability in the distributions; in some years the salmon appear to be more confined to the coast, while in other years they are distributed further offshore. In all cases however, the maps suggest a northwestward drift of fish from Kuskokwim/Bristol Bay. Although many factors may account for the year-to-year differences in fish distributions, some of this variability is due to variations in the flow field.

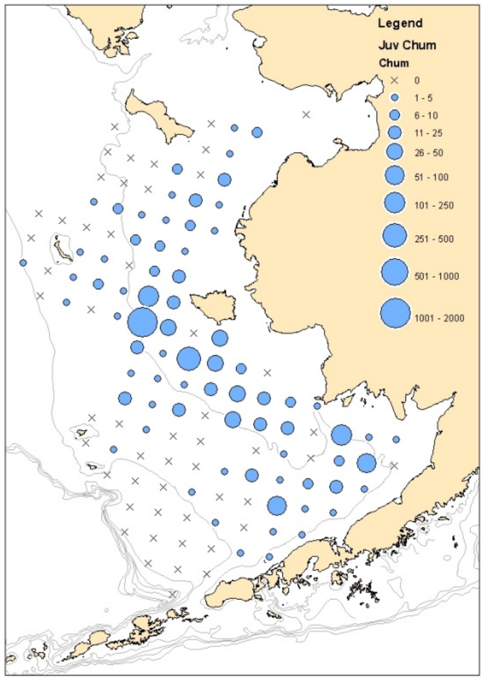

Figure 4. Juvenile chum salmon distribution in the Bering Sea from August-October, 2005 (http://www.afsc.noaa.gov/abl/occ/basis.htm).

IV. OBJECTIVES:

Project Objectives

The overall goal of this project was to improve our understanding of the nearshore circulation field that connects Kuskokwim Bay and northern Bristol Bay with the adjacent Bering shelf. This information is needed to understand the possible migratory pathways and habitats used seasonally by juvenile salmon as they enter the marine environment. Our specific goals are to:

1. Determine the seasonal (summer through fall) character of the nearshore circulation field and its connection to the adjacent shelf;

2. Establish a suite of statistical estimates that characterize the kinematical properties of the flow field in relation to seasonal variations in wind and coastal freshwater discharge;

3. Use the results of step 2 to hindcast likely salmon transport pathways based on satellite measurements of the Bering Sea wind field.

4. Work with residents of western Alaska (Quinhagak) to conduct the field programs.

Contribute collaboratively to the efforts of other ongoing and planned programs. These include the BASIS program and the BEST-BSIERP program jointly funded by NSF and NPRB.

Objective 3 was modified due to the failure of the QuikSCAT satellite in 2009. Instead of using satellite estimates of the wind field, we relied upon winds from the National Center for Environmental Prediction (NCEP) Re-Analysis effort. These have the advantage over QuikSCAT in that they are available four times per day and can be used for retrospective analyses, since they begin in 1949. They lack the horizontal resolution of QuikSCAT however since NCEP winds are available on a 2.5 x 2.5 degree grid whereas QuikSCAT has a 25 km resolution but only available twice per day. There are no statistical differences in the wind products between the two wind fields however (*Mull* et al., 2007).

This information is critical in understanding what factors affect survival from the smolt through the early marine stages and how survival during this period is affected by physical forcing associated with winds and runoff. Our objectives will quantify the circulation characteristics of what appears to be the most likely migratory pathway undertaken by young salmon upon exiting Kuskokwim Bay. The results can provide: 1) estimates of the residence time of juvenile salmon over various portions of the shelf, and in particular the nearshore environment, 2) estimates of the advective time scales associated with transporting salmon from the mouth of the bay to various portions of the shelf, and 3) an understanding of the processes involved in transporting salmon offshore or trapping them inshore.

V. METHODS:

Methods

The measurement approach consisted of deploying clusters of ~4 satellite-tracked drifters in lower Kuskokwim Bay (approximately 60 miles southwest of Quinhagak, [**Figure 1**]) at ~10- to

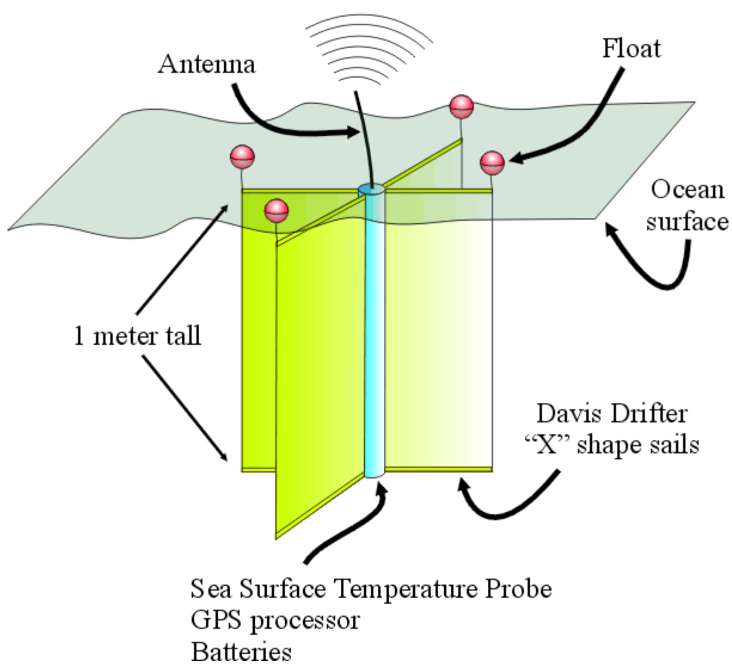

Figure 5. A sketch of the CODE or Davis drifter used in this circulation study.

15-day intervals between June and September (October) 2008 and 2009. 32 drifters were deployed in each year. Drifter positions and ocean temperatures are determined by satellite GPS fixes twice (or more) per hour, stored aboard the drifter and then transmitted via Service Argos once a day. We received about 30 fixes/day, which was sufficient to resolve the semi-diurnal (M_2) tidal currents. We deployed the Davis or CODE-type drifters (**Figure 5**), which consists of two whip antennae (for ARGOS transmission and GPS fixes), a bi-planar drogue of 1-meter length mounted about the electronics case and centered at 1 m depth, and a temperature sensor installed at the base of the case. Since young salmon spend most of their time near the surface, the 1-m drogue guaranteed that we are measuring the currents at the depth they typically inhabit. Drifter performance characteristics [*Davis*; 1985a] indicate that drifter slippage is ~1 cm s^{-1} and thus small compared to magnitudes of the 10 – 100 cm s^{-1} tidal velocities typical of the region and the 5 – 50 cm s^{-1} wind-forced currents [*Kinder and Schumacher*, 1981; *Danielson et al.*, 2006]. Drifter battery life is nominally nine months, but freezing, sea ice, and rough seas shorten drifter lifetime and most of our drifters ceased transmitting by late November.

Deployments were cost-effectively and efficiently executed by the residents of Quinhagak and typically engaged schoolchildren from the village (**Figures 6 and 7**).

Figure 6. Quinhagak schoolchildren readying a drifter for deployment in Kuskokwim Bay.

Figure 7. Quinhagak schoolchildren deploying a drifter in Kuskokwim Bay.

Figure 8. Photograph of an activated drifter shortly after being released from its cardboard container. Note the two antennae and the small surface signature of the drifter.

Deployment consists of slipping a magnetic reed switch from the outside of cardboard box, which activates the drifter contained in the box. The box is then slipped into the water with the cardboard dissolving within about 20 minutes of launching. The drifter then unfurls and begins its mission (**Figure 8**). After deployment we monitored the drifter's motion daily and posted the results on the project website (http://mather.sfos.uaf.edu/drifters/). On a daily basis we mapped and updated the drifter's trajectory forming cumulative histories of the drifters' trajectories and data as exemplified in **Figures 9 - 11** for drifter #D81018. The website also includes animations for several of the drifters and additional information on the project.

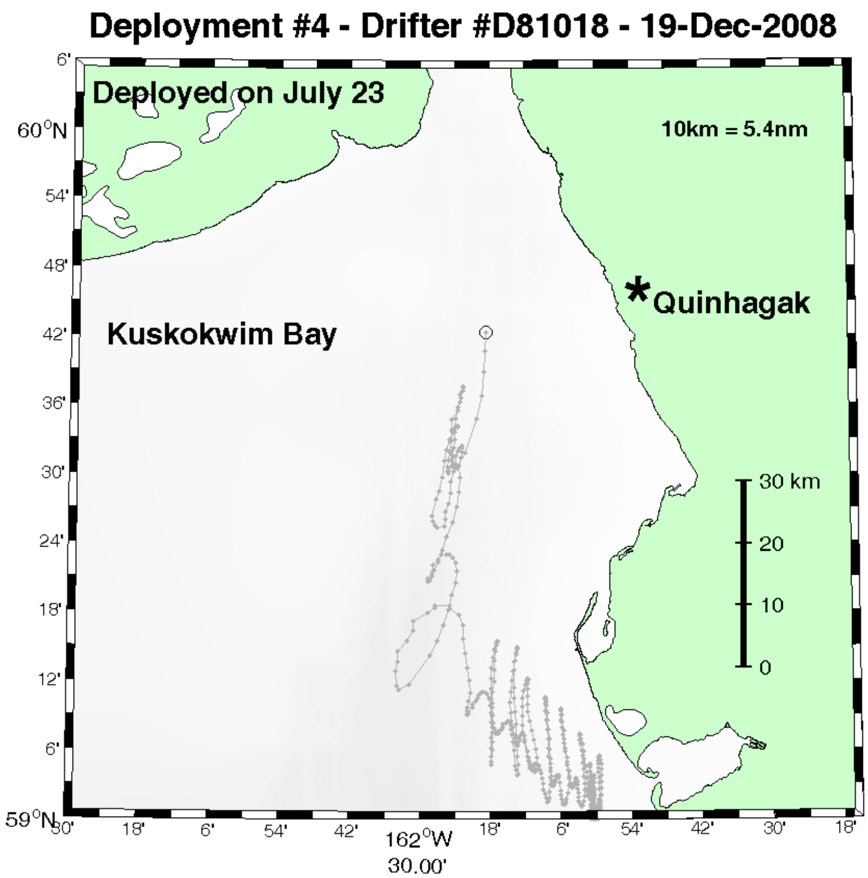

Figure 9. Trajectory of Drifter #D81018 deployed on July 23, 2008. The large oscillatory excursions are associated with semi-diurnal (M2) tidal motion. This view shows the first week of this drifter's trajectory as it moved southward in Kuskokwim Bay. These high-resolution plots were used during the initial portion of the drifter's track to enable close inspection of the drifter's behavior in Kuskokwim Bay.

Figure 10 shows the entire trajectory of drifter #D81018. The drifter reached the mouth of the bay by late July, and then appeared to reside in an eddy at the bay's mouth for about 10 days, before moving southward and offshore onto the shelf. (There is also anecdotal evidence for this eddy by fishermen working in this area as related to us by Marine Advisory Program agent Mr. Terry Reeve.) Thereafter it slowly drifted southwestward toward the Pribilof Islands before expiring on Jan 8, 2009. **Figure 11** shows time series of the latitude, longitude, and temperatures measured by Drifter 81006. Note the occasional spikes in position (October 23) and temperature (October 9) and the decay in position data towards the end of this drifter's life (December 2008). Each of these spikes were edited prior to final analyses and gappy drifter fixes were either interpolated or discarded if close to the end of the drifter's life.

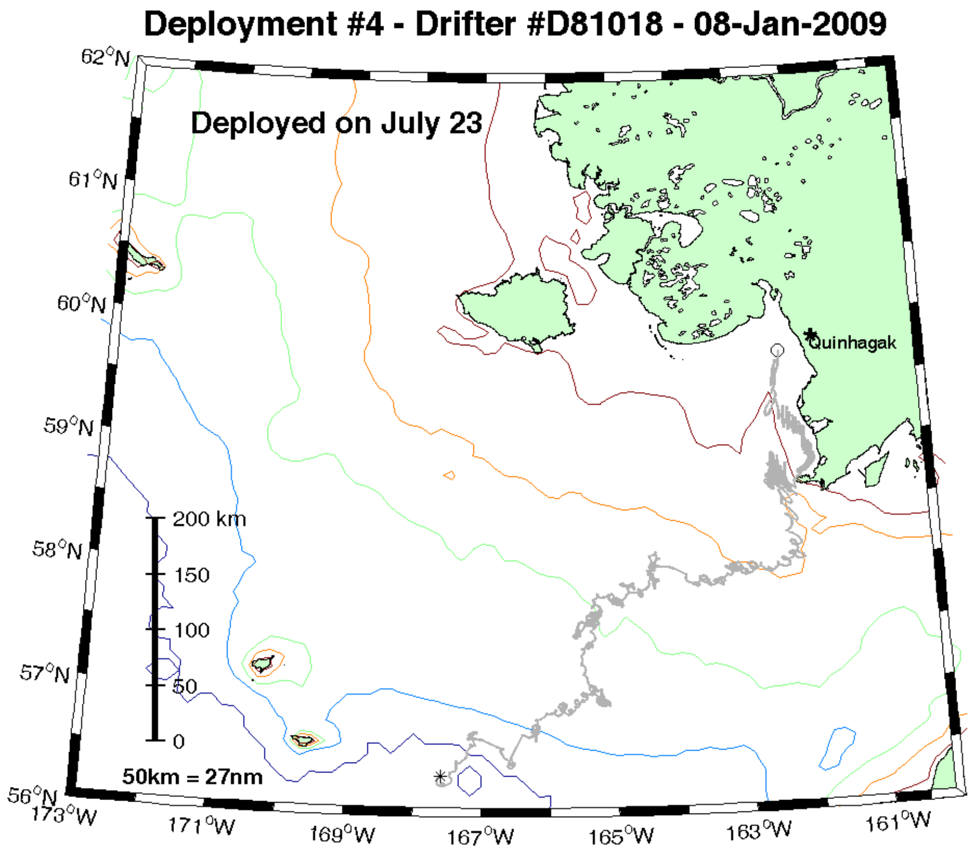

Figure 10. Entire trajectory (July 23, 2008 – January 8, 2009) of drifter #D81018. Small oscillatory motions are primarily tidal, whereas larger excursions are primarily associated with the winds. (This is an example map, which was automatically update daily and posted on the project webpage. The data are raw and unedited.)

After data editing drifter positions and temperatures were referenced to a common time base (e.g., half-hourly). East-west and north-south velocities were derived by central differencing successive fixes. Tidal velocities were estimated by least squares harmonic fits to the M2 and K1 tidal constituents, which are the largest tidal components on the Bering Sea shelf. **Figure 12** shows the edited trajectory and time series of the velocity and temperature data from the drifters. The velocity component time series include both the velocities with (blue) and without (red) the tidal components included. Note that the scales for the velocities are different; those which include the tidal components range between -4 and +4 m/s, whereas the detided time series range between -8 and +8 cm/s. The difference in scales reflects the fact that the tides are the dominant source of current kinetic energy on the shelf.

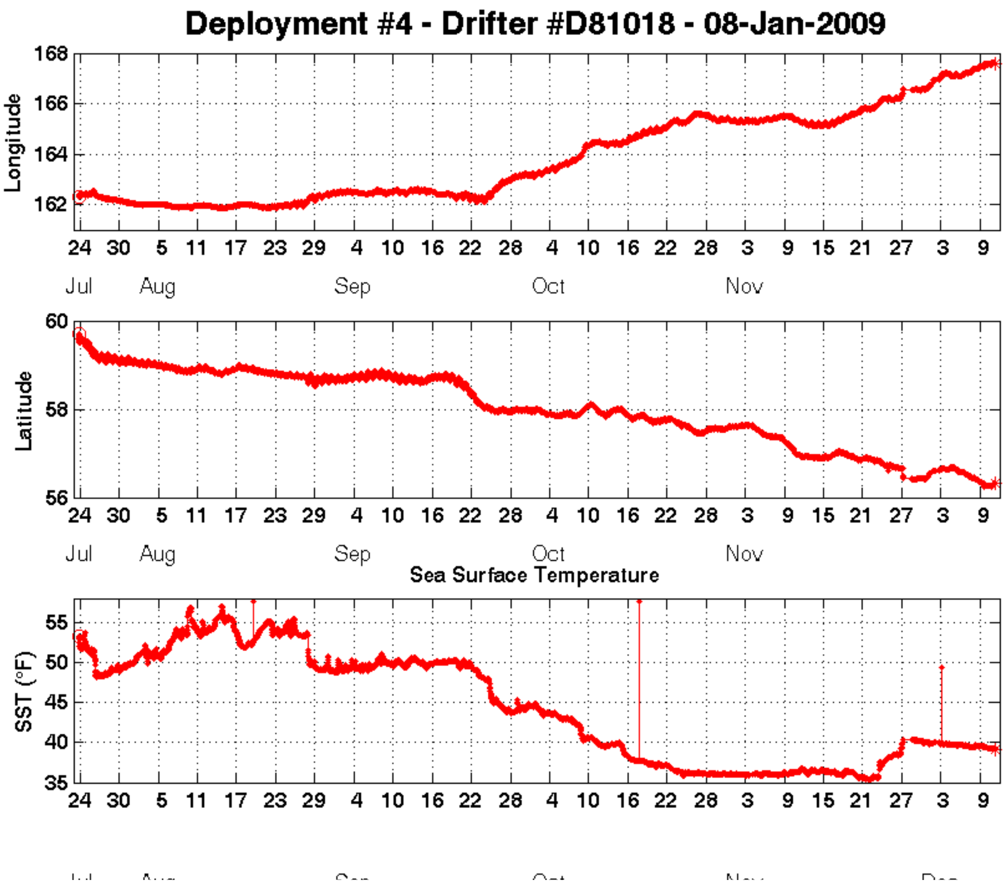

Figure 11. Example of time series of the raw data transmitted by the drifter via Argos satellite. The drifter was deployed on July 23 and ceased transmitting on Jan. 8, 2009. Note that the spikes in the temperature record were eliminated before final processing. (This is an example time series, which was automatically update daily and posted on the project webpage. The data are raw and unedited.)

The temperature time series largely reflects the seasonal change (decrease) in temperature due to atmospheric cooling. Thus temperatures exceed 15°C in summer in the upper Bay, but decrease moving offshore through fall until encountering slightly warmer waters over the outer shelf. (**Figures 17** and **19** also show how the sea surface temperatures increase over the shelfbreak).

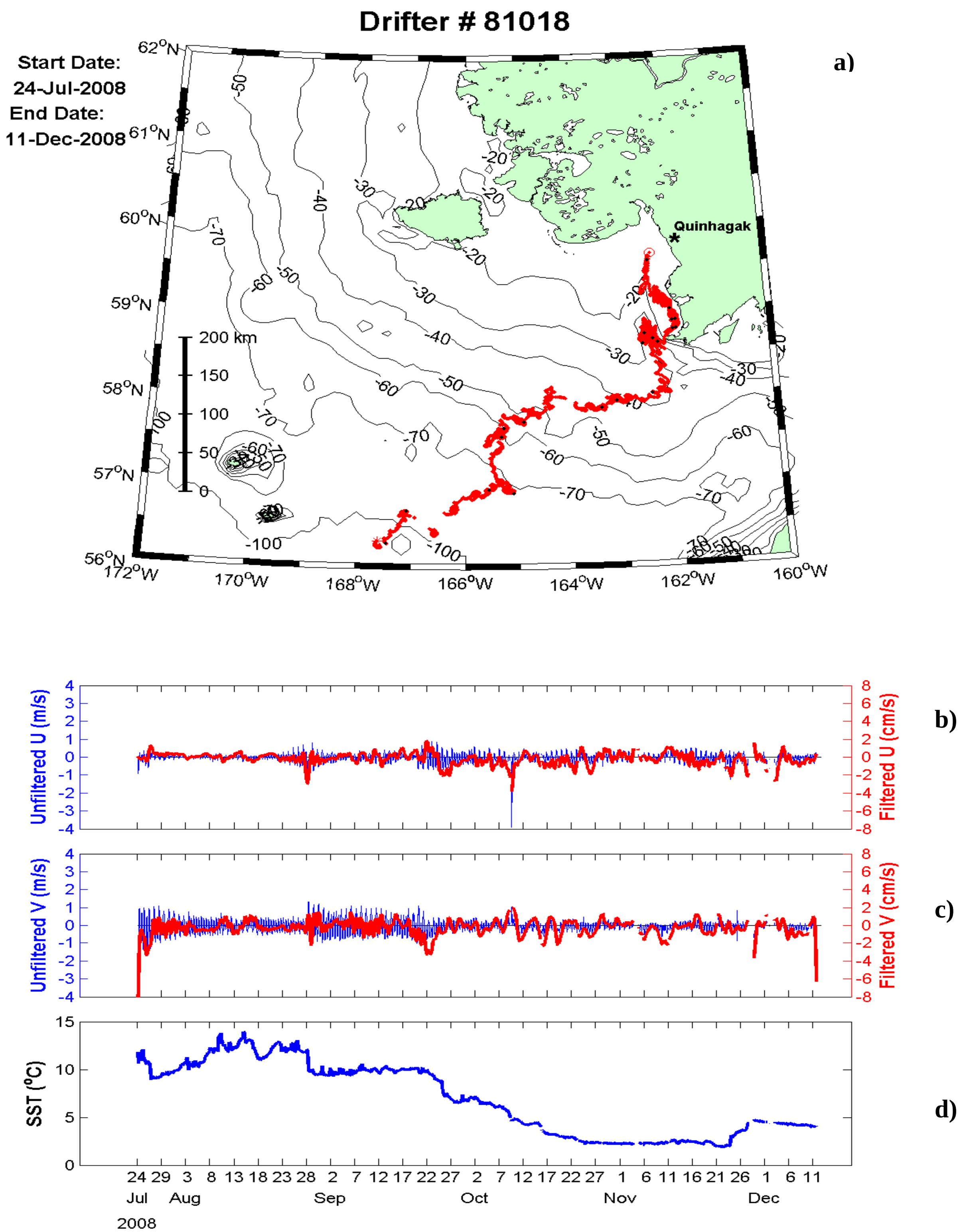

Figure 12. Trajectory (a) and filtered (red) and unfiltered (blue) zonal (b) and meridional (c) velocity components and sea surface temperature (d) for drifter 81018. (Black dots on the trajectory map represent days that are a multiple of five, i.e. August 30, September 5, etc.)

VI. RESULTS:

Results and Discussion

Detailed results from this project are being incorporated into a graduate student's thesis and for publication in a peer-reviewed journal. Herein we provide an overview of the main results.

We begin by illustrating the seasonal variations in winds over the Bering shelf based on composite QuikSCAT monthly winds for July, September, and November shown in **Figure 13**.

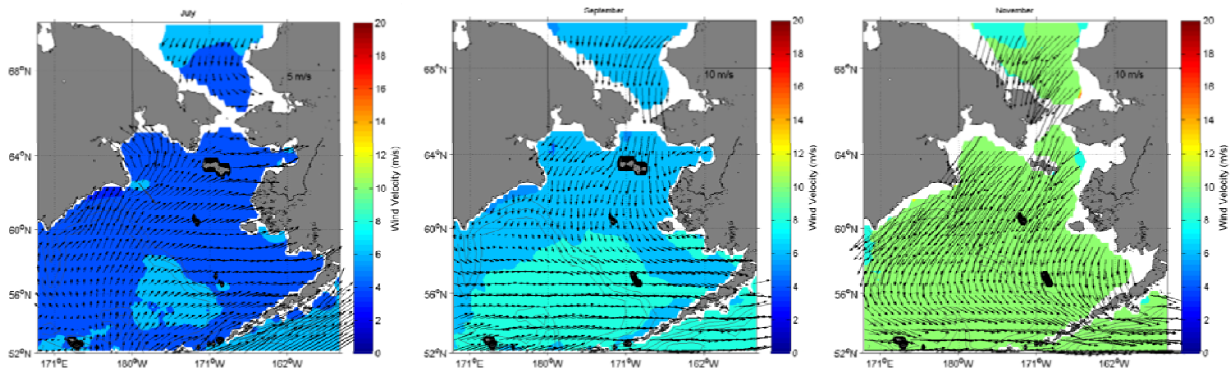

Figure 13. Mean monthly winds for July, September, and November based on the QuikSCAT satellite (from *Mull et al.*, 2007).

Summer winds (July) are weak and variable with the mean winds over the southern Bering Sea being from the southwest and west. By September wind speeds increase and veer from the north over the northern Bering Sea shelf while being from the west over the southern portion of the shelf. Winds continue to strengthen through the fall and are from the north over the entire shelf from October – December (and through winter). Winds blowing such that the coast is to the right of the wind direction (from the north over the northern shelf and from the west over Kuskokwim Bay) impel a surface offshore transport that is proportional to the square of the winds speed. Hence based on the mean wind fields we expect that surface waters should move, on average, offshore (upwelling) unless countered by other forces. Those other forces include pressure gradients established by horizontal differences in water density. For example, the buoyant water emanating from a river will set up pressure gradients because low-salinity, low-density water is adjacent to the coast, while saltier (more dense) water occurs offshore. In this case the pressure gradient will tend to drive an alongshore flow with the low-salinity (and coast) to the right of the direction of motion. Hence, when considering the winds and river runoff together these forced tend to compete with one another on the shelf adjacent to Kuskokwim Bay.

Figure 14 shows a composite map of all drifter trajectories for the 2009 field program. (The results from 2008 were very similar and not shown.) Note the general west-southwesterly drift of most of the drifters deployed in upper Kuskokwim Bay. Several of these drifted to the north and northwest through Etolin Strait and thence northward along the coast. One drifted nearly into Norton Sound before turning southward and moving toward St. Lawrence Island before terminating. Several of the drifters made it nearly to the Pribilof Islands and one crossed the shelfbreak before turning northwards along the continental slope.

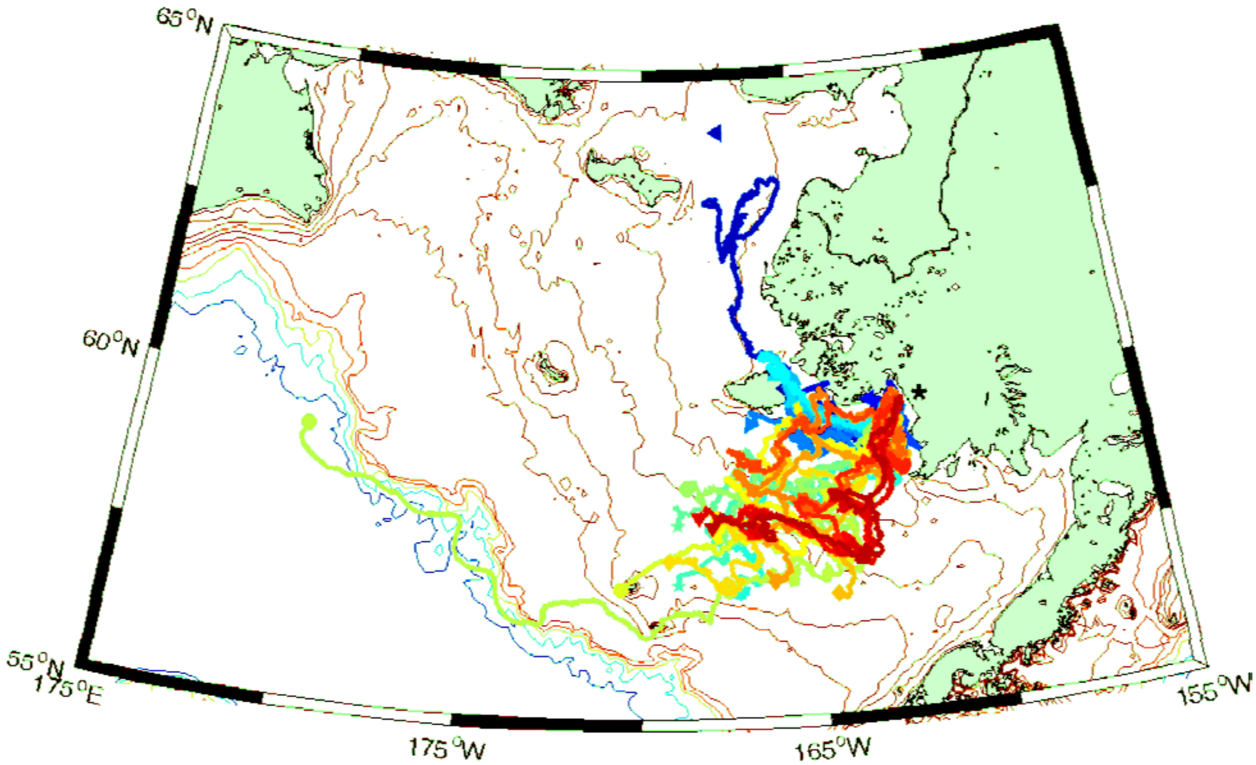

Figure 14. Composite drifter trajectories from 2009.

Figure 15 shows maps based on the the M2 tidal analyses (left panel) and the mean surface vectors (right panel) computed from the detided velocities. These were derived by binning all drifter measurements within a 27 x 27 km box, or roughly 4 boxes per degree of latitude. The tidal velocities are presented in terms of tidal ellipses, which show how the magnitude and the orientation of the M2 tide varies spatially. Ellipses that are thin and elongated indicate nearly rectilinear (back and forth) motion, whereas nearly circular motion indicates that tidal currents have nearly uniform magnitude over the course of the tidal cycle. In general the tides vary from being relatively small and circular offshore to being more eccentric and stronger inshore. Large tidal currents and nearly rectilinear motion occurs around much of Nunivak Island and within the north-south channel that comprises Kuskokwim Bay where the tidal currents are ~1 m/s and oscillate primarily along the axis of the channel.

The mean surface flow (**Figure 15** right panel) indicates a generally westward drift of all drifters (similar in both years) across the shelf. Within Kuskokwim Bay this drift is southward toward Cape Newenham and consistent with an estuarine-type circulation in which fresh surface waters move out of the bay and more saline shelf waters flow inshore below the surface. To the west of the Bay, the flow is westward along the coast into Etolin Strait and/or westward along the south coast of Nunivak Island. Throughout the rest of the region the flow is southwestward. Mean currents are weak and average ~5 cm/s. The strongest mean currents are ~10 cm/s and occur in the surface layers of Kuskokwim Bay.

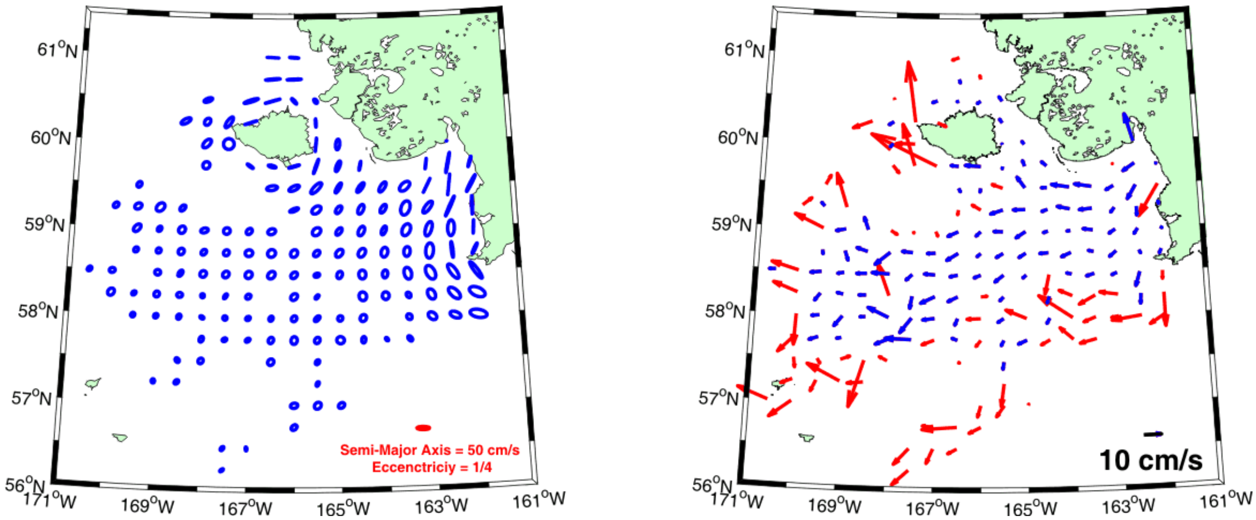

Figure 15. Left panel shows the distribution of the M2 tidal ellipses averaged from all drifters within ~30 km boxes. The right panel shows the mean surface velocity computed from all drifter measurements within the same box. Red vectors are uncertain and include less than 10 measurements within the box.

The averaging masks the seasonality of the flow field however. Inspection of each drifter trajectory suggested that the flow field differed between summer and fall and this impression was borne out by averaging velocities from June through August and from September through January. Indeed as shown in **Figure 16,** the flow does vary seasonally.

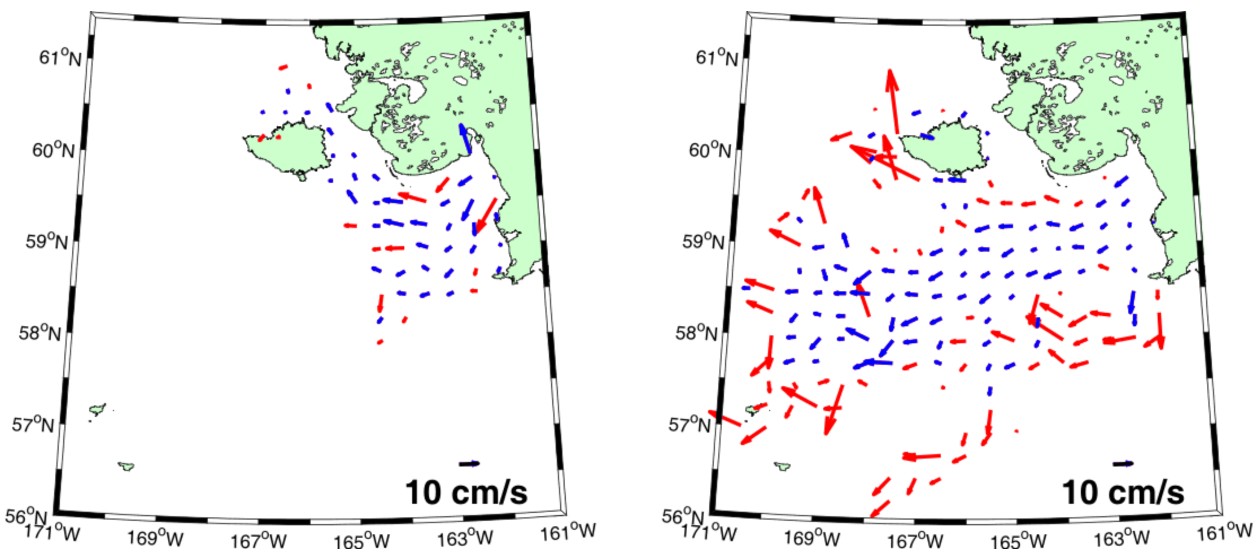

Figure 16. Mean June-August (left) and September – January (right) surface vectors derived from all drifters. Red vectors indicate average based on 7 or less drifter-days of data within the averaging box.

From June – August the flow is largely trapped to the coast, with a general movement westward toward and through Etolin Strait. Between September and January, the flow continue westward out of Kuskokwim Bay but is deflected seaward and towards the central shelf instead of towards Etolin Strait. The June-August circulation pattern is consistent with buoyancy-driven coastal dynamics, e.g., the mean circulation of cross-shelf density gradients established by a river outflow onto a shelf and subject to the Coriolis acceleration. The broadscale (~100 km wide westward flow in summer is consistent with this notion, although it is also influenced by winds and tides. In contrast the September through January circulation is decidedly offshore and to the west/southwest in accordance with the strong upwelling-favorable winds that prevail during these months. While the mean current speeds in both seasons are similar, the flow direction is markedly different.

Analyses of the temperature and salinity measurements collected during the National Science Foundation's BEST program (Weingartner, unpublished data) indicate that there is a front in summer along about the 20 m isobath (~100 km southwest of Kuskokwim Bay). The front is also evident in regional thermal infrared satellite imagery of sea surface temperatures, examples of which are shown in **Figure 17 - 19**. Note that the July image (**Figure 17**)suggests the presence of two fronts, one very close to shore separating waters of 12 – 14^{o}C from waters of 8 – 10^{o}C and a second front, farther offshore separating waters of 8 – 10^{o}C (along about the 20 m isobath) from mid-shelf waters of ~3 – 5^{o}C. Motion along fronts tends to be enhanced, whereas flow across fronts tends to be inhibited. Hence the fronts would tend to trap low-salinity (~30 or less) coastal waters inshore in summer. The fronts likely erode through fall as cooling begins, winds intensify, and river discharge weakens.

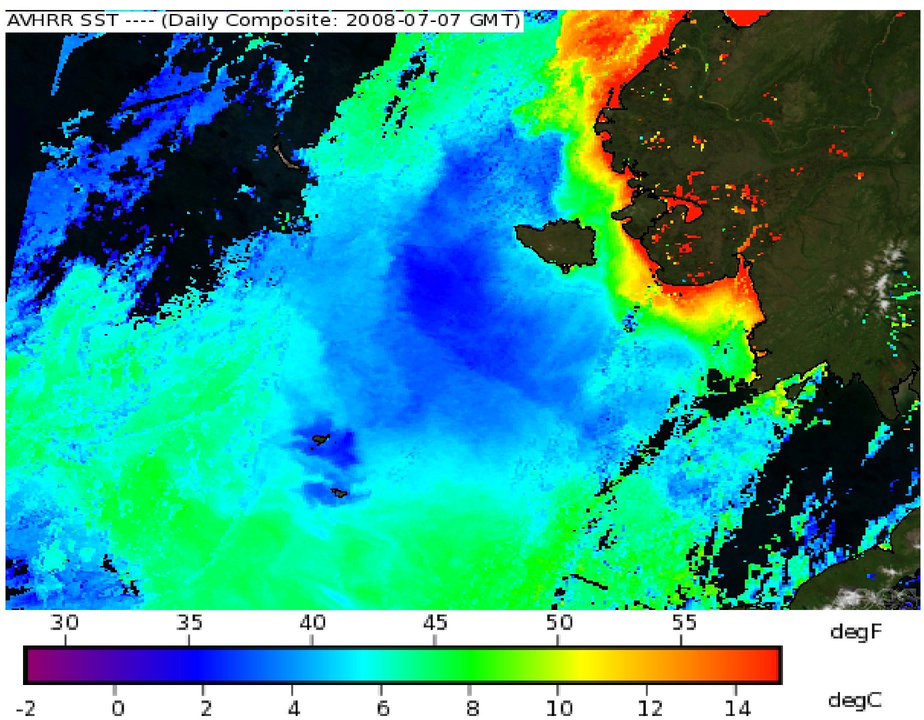

Figure 17. Satellite thermal infrared red imagery of sea surface temperatures over the Bering Sea shelf on July 7, 2008.

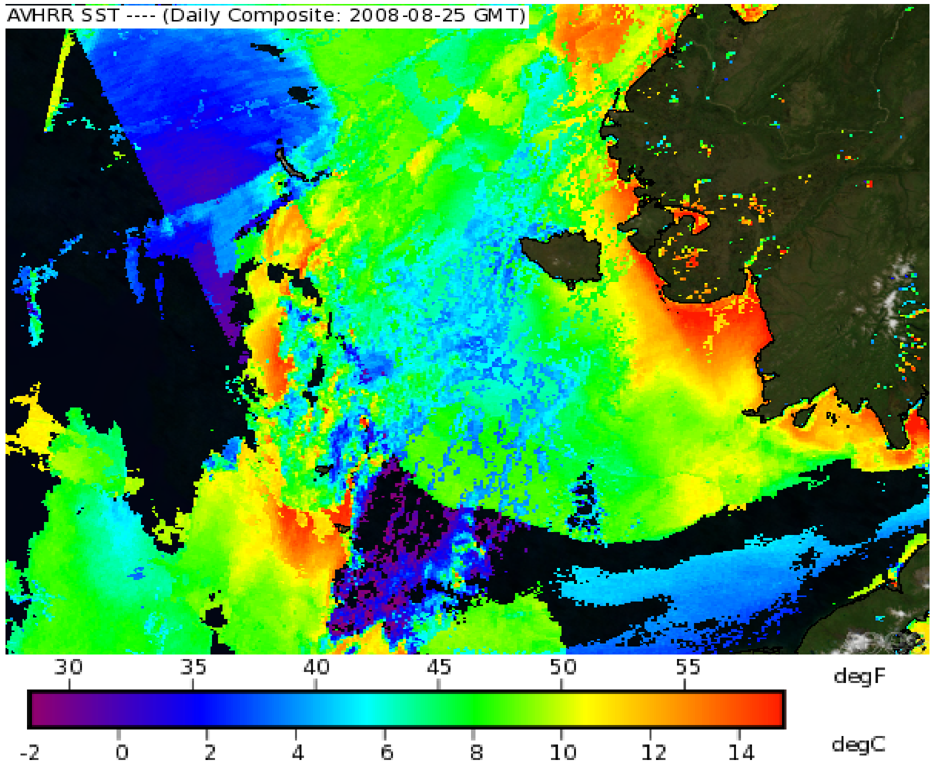

Figure 18. Satellite thermal infrared red imagery of sea surface temperatures over the Bering Sea shelf on August 8, 2008.

The August image (**Figure 18**) suggests that the inner most front has weakened, although that along about the 20 m isobath is still intact. However, by October (**Figure 19**) the fronts have weakened considerably over the shelf. In fact, there is a band of very cold water extending southward along the coast and into Kukokwim Bay. This band may be related to upwelling and/or southward advection of cooler waters from the northern Bering Sea.

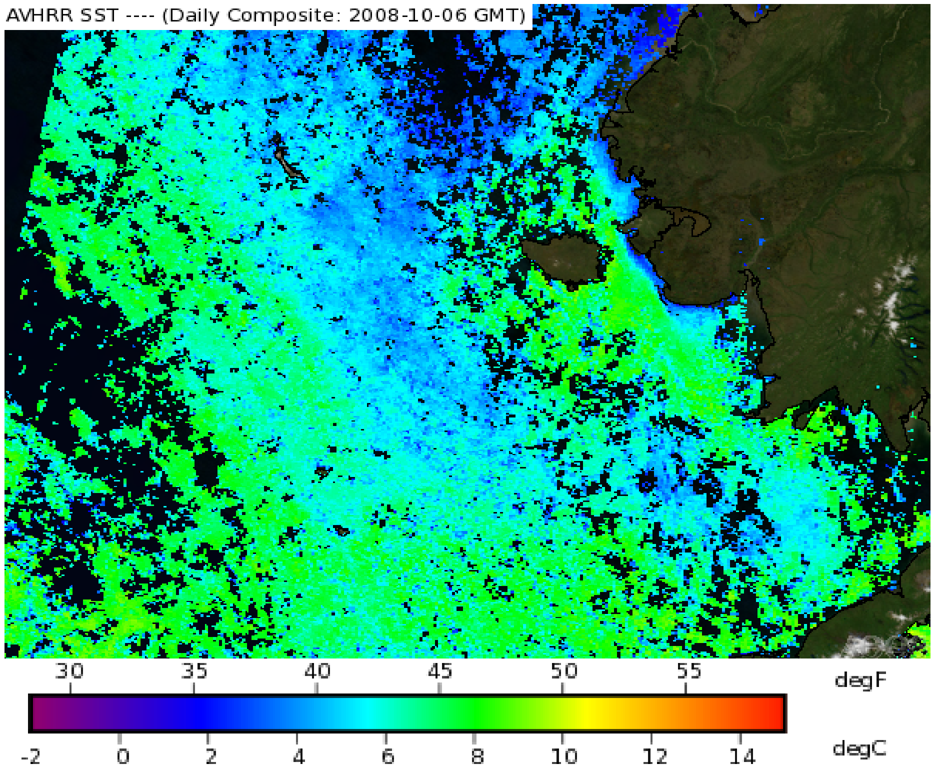

Figure 19. Satellite thermal infrared red imagery of sea surface temperatures over the Bering Sea shelf on October 10, 2008.

The low salinity waters inshore of the front are nitrate-poor (**Figure 20**) and cannot support biological production. This of significance to outmigrating juvenile salmon, since those carried westward along the coast are unlikely to find sufficient prey for successful feeding. In contrast the estuarine circulation with the Kukokwim Bay channel may advect sufficient numbers of zooplankton and/or nutrients into the Bay to create successful foraging opportunities. Similarly if the juveniles are carried offshore (as expected) in fall, they should encounter substantial prey over the central shelf. In aggregate the drifter trajectories indicate that low-salinity, nitrate-poor coastal waters are carried offshore and into the middle and outer domains of the Bering Sea shelf in fall. Since the mean flow in these regions is small it is likely that this coastal water remains over the mid- and outer shelves through winter and into spring. Offshore dispersal of coastal waters, as observed by the drifter trajectories in both years, may therefore play an important role in the annual nutrient budget of this shelf. As such it will also affect the biological productivity of these portions of the shelf, which are also used by juvenile salmon as they make their way to sea.

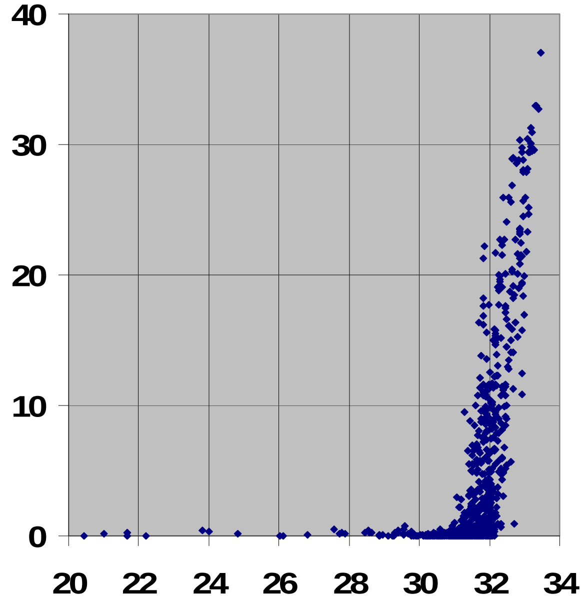

Figure 20. The nitrate-salinity relationship for Bering shelf waters (Danielson et al., in press).

On the basis of our understanding of the hydrography, bathymetry and the observed seasonality of the flow we decided to analyze the drifters in three separate regions:

1. Water depths < 30m but to the west of the main channel in Kuskokwim Bay,
2. Water depths > 30m and in the Kuskokwim Bay channel,
3. Water depths > 30m.

Our rationale for this division is as follows. Bottom depths >30 m occur seaward of the inner domain and are usually characterized by stratified waters and relatively small tides. Water depths <30 m and outside the channel are presumably well-mixed (and unstratified) due primarily to the strong tides and shallow depths. Moreover, motions here are not likely constrained by channel topography. Drifters within the channel are probably influenced by the bottom topography and this region may be occasionally stratified by a presumed estuarine-type circulation. (In this scenario, salty offshore waters migrate inshore with the tides and are vertically-mixed with the river outflow. This mixture flows (on average) down channel.

With these *a priori* divisions we assessed the wind-current relationship for all drifters by least squares fits to equations of the form:

$$U(t)_{drifter} = a_u U(t)_{wind} + b_u V(t)_{wind} + c_{u\,mean}$$

$$V(t)_{drifter} = a_v U(t)_{wind} + b_v V(t)_{wind} + c_{v\,mean}$$

Where $U(t)_{drifter}$ is the east-west (zonal) and $V(t)_{drifter}$ is the north-south (meridional) component of the drifter velocity and $U(t)_{wind}$ and $V(t)_{wind}$ are the zonal and meridional components of the wind. The term c_{xmean} (where $x = u$ or v) are the residual velocities, which we ascribe to the mean background velocity field. The coefficients of the regression are a_x, and b_x, where (where $x = u$ or v). The regression results for each region are given in **Tables 1 - 3**. For water depths $\geq$30 m, only drifter measurements obtained between August and December were included in the regressions since there were few points (<200) in other months and these were often associated with only 1 drifter. The regressions in Table 1 are statistically significant at the 95% confidence level and account for about 50% of the variance. These results are encouraging in that they imply that the historical NCEP winds can be used to assess drift between August and December for the southeast Bering Sea. The regressions also indicate that the drifters move to the right of the wind at between 30 and 45 degrees, in basic agreement with Ekman dynamics.

Table 1. Wind-current regression statistics for water depths $\geq$30 m (August – December). The subscript "*x*" implies either "*u*" or "*v*".)

	$U(t)_{drifter}$		$V(t)_{drifter}$	
	Coefficient	Error	Coefficient	Error
a_x	0.0132	0.010	-0.0079	0.0116
b_x	0.0076	0.0074	0.0079	0.0088
c_{xmean} (m/s)	-0.054	0.0574	0.0025	0.0592
r^2	0.50		0.59	
# of points	7535			

The regressions for the inshore region (**Table 2**) and the channel (**Table 3**), while still significant, explain a smaller fraction of the variance in each velocity component. This is not unexpected given our expectations that buoyancy forces in both region will affect the dynamics. Note also that our efforts to completely remove the tides in these regions were not completely effective. We used a fourth-order Butterworth filter to suppress fluctuations at diurnal and shorter periods. However, this filter still passes about 4% of the diurnal tidal energy. Since the subtidal motions are still weak, this noise may degrade the regressions. We are presently re-analyzing the data with different filter types in an effort to better suppress the tidal influence.

Table 2. Wind-current regression statistics for water depths $\geq$30 m (August – December).

	$U(t)_{drifter}$		$V(t)_{drifter}$	
	Coefficient	Error	Coefficient	Error
a_x	0.0082	0.008	-0.007	0.0064
b_x	0.0013	0.005	0.0088	0.0046
c_{xmean} (m/s)	-0.030	0.038	0.018	0.030
r^2	0.38		0.47	
# of points	5353			

Table 3. Wind-current regression statistics for Kuskokwim Channel (August – October).

	$U(t)_{drifter}$		$V(t)_{drifter}$	
	Coefficient	Error	Coefficient	Error
a_x	0.0078	0.0076	0.001	0.005
b_x	-0.0066	0.006	0.008	0.004
c_{xmean} (m/s)	-0.03	0.0305	0.018	0.026
r^2	0.37		0.44	
# of points	3709			

Following *Poulain and Niiler* (1989) we have also computed the discrete auto-correlation functions (acfs) for the drifters in each domain separately and for each velocity component according to:

$$\frac{1}{u_{rms}^2}\sum_{t=0}^{N-\tau} u'(t)u'(t+\tau)$$

Where u_{rms}^2 is the root mean square of the velocity component, $u'(t)$ is the departure of the velocity component at time *t* from its record length mean and $u'(t+\tau)$ is the velocity deviation at time *t*+τ. **Figure 21** shows an example of the acfs for several individual drifters as well as the mean acf for all drifters seaward of the 30 m isobath.

From the acf we can compute the Lagrangian time scale (T_x) defined as $T_x = \tau_{zero}(\Delta t)$ where $\tau_{zero}(\Delta t)$ is the time in hours of the first zero crossing of the acf. The zonal Lagrangian time scale (T_u) for the mean acf in **Figure 21** is ~5 days, while the meridional Lagrangian time scale (T_v) is ~2 days. The Lagrangian length scale in the zonal direction is defined as $L_u = u_{rms}T_u$ and also a function of the acf. Our data suggests that this length scale is ~38 km in the zonal direction and 16 km in the meridional direction so that the motions are anisotropic. These scales define the time and distance over which drifter observations decorrelate from one another. In other words, all drifters within an east-west (north-south) distance of 35 km (20 km) for time periods less than T_u (T_v) do not represent independent measurements. These scales are relevant when considering sampling strategies for drifting organisms. For example, if juvenile salmon are following plankton patches, then these patches are moving independently from one another if their separation in time and space exceed the Lagrangian time and space scales. The results of these calculations are summarized in **Table 4** for all domains.

We have also included estimates of the eddy zonal and meridional diffusivities, defined as: $K_{xx} = u_{rms}^2 T_u$ and $K_{yy} = v_{rms}^2 T_v$. Outside of the channel the zonal diffusivities are about twice those of the meridional diffusivities, whereas within the channel K_{yy} is about 30% larger than K_{xx}. We suggest that these differences reflect the influence of the channel bathymetry.

The diffusivities allow us to estimate the relative role of advection and diffusion in the heat and salt budgets of the middle shelf of the Bering Sea. Historical hydrographic data (*Danielson et al.*, in press) allows us to make these comparison for the region seaward of the 30 m isobath since dating inshore of this isobath is lacking. Hence we compare the relative magnitudes of the cross-shore diffusive and advective terms, e.g.,

$$\frac{K_{xx}\dfrac{\partial^2 S}{\partial x^2}}{u\dfrac{\partial S}{\partial x}} \approx \frac{3450\dfrac{m^2}{s}\left(1.25x10^{-11}\dfrac{psu}{m^2}\right)}{.05\dfrac{m}{s}\left(1x10^{-5}\dfrac{psu}{m}\right)} \sim 0.1$$

So that the advective contribution to the salt (and nutrient budget) is an order of magnitude more important than cross-shelf diffusion. Repeating the calculations for heat suggests that diffusion and advection are of comparable magnitude at least in summer when the temperature gradients are largest.

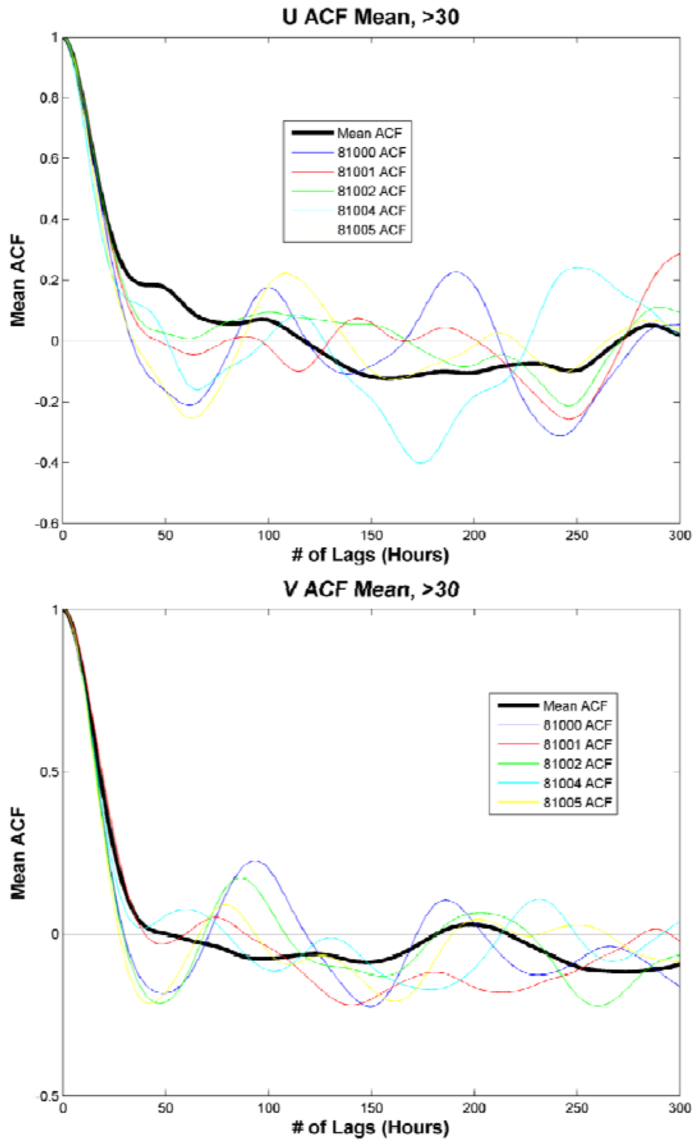

Figure 21. The autocorrelation function for the zonal (top) and meridional velocity components for all drifters seaward of the 30 m isobath (thick solid line). Acfs for several of the drifters are shown by the light lines.

Table 4. Summary statistics derived from drifter measurements in the three domains. Numbers in parentheses are the 95% confidence limits.

	Offshore 30 m isobath	Inshore 30 m isobath	Kuskokwim Bay Channel (<30m)
u_{mean} (m/s)	-0.03 (0.006)	-0.03 (.005)	-0.04 (0.009)
u_{rms} (m/s)	0.089	0.086	0.089
u^2_{rms} (m^2/s)	0.008	0.007	0.008
T_u (days)	5	4.2	2
L_u (km)	38	31	15
K_{xx} (m^2/s)	3450	2540	1380
v_{mean} (m/s)	-0.01 (0.008)	-0.006 (0.006)	-0.02 (0.01)
v_{rms} (m/s)	0.095	0.089	0.114
v^2_{rms} (m/s)^2	0.009	0.008	0.013
T_v (days)	2	2	1.7
L_v (km)	16	15	17
K_{yy} (m/s^2)	1560	1380	1900

VII. DISCUSSION:

Our results show a distinct seasonal pattern in the nearshore circulation. In summer (June – August) waters from upper Kuskokwim Bay appear to flow along two distinct pathways; moving westward in a buoyant coastal current inshore of the ~20 m isobath or southward to lower Kuskokwim Bay toward Cape Newenham. Very likely the latter behavior reflects estuarine circulation (and tides) largely confined to within the channel that runs along the north-south axis of Kuskokwim Bay. (We emphasize that our definitions of inside and outside of this channel are subjective insofar as the regional bathymetry is poorly known and consequently determining which pathway a drifter might take is not possible with the existing data.) Drifters that moved southward down the channel were often trapped in an eddy-like feature at the mouth of the bay before moving southward and offshore onto the shelf. Drifters that moved westward along the coast typically entered Etolin Strait between the mainland and Nunivak Island in summer. However, by late August or September, increasing northerly winds resulted in all drifters moving toward the west southwest consistent with Ekman dynamics. This offshore motion likely coincided with the breakdown of a density front along about the 20 m isobath of the inner shelf. Once seaward of this isobath all drifters moved westward. All drifters released after August tended to move offshore (southwestward and westward) across the 20 m isobath relatively rapidly. Salmon drifting with the *mean* flow will take about 1 month to reach Etolin Strait and about 3 months to reach Cape Newenham at the entrance to Kuskokwim Bay.

To the extent that juvenile salmon follow the water motion our results suggest that juveniles moving westward and close to the coast in summer will likely encounter poor food supplies, since inner shelf waters are nitrate-poor and unlikely to support phytoplankton (and zooplankton production). Salmon moving southward in the bay may find better foraging if the presumed estuarine circulation in the bay can transport nutrients and plankton from the shelf and into the bay. The inferred eddy offshore of Cape Newenham and at the mouth of the bay may aggregate prey and thus be a foraging area for these young fish. Presumably once the salmon migrate offshore (beyond the 20 m isobath) and into the saltier (and more productive) shelf waters, foraging success is enhanced.

We suggest a simple way to test this hypothesis. Juvenile salmon should be sampled at the mouth of the Kuskowkim River prior to their entry into the bay and their body condition ascertained. Juvenile fish should also be collected at the mouth of the bay and in Etolin Strait and their body condition compared with one another and with the juveniles entering the head of the bay. If our hypothesis is correct then juvenile salmon body condition should be better at the mouth of the bay than in Etolin Strait. If this is indeed the case, then recruitment success for salmon may depend upon the proportions of juveniles that move westward along the coast rather than southward along the main channel of Kuskokwim Bay. The Lagrangian time and space scales suggest that independent samples of organism drifting with the flow are separated by about 4 days (or 30 km) in the east-west direction over the inner portion of the shelf west of Kuskokwim Bay and by 2 days and/or 17 km in the Kuskokwim Bay channel. Hence from the physical perspective, the sampling in both places could be done at weekly intervals to insure independent measurements.

An important result of this study is the recognition that it could not have been achieved efficiently without the involvement of Quinhagak residents. The drifter deployments were conducted quickly and safely throughout the entire study. We had similar success with a smaller pilot study conducted from Mekoryuk in September 2003, and that success motivated this effort. We are convinced that additional and more complicated sampling can be conducted successfully by the residents of western Alaska. For example sampling of juvenile salmon to determine length-frequency and condition indices could be conducted routinely by trained residents. Villagers could be trained to make many standard measurements and then forward the samples to the laboratory for more complicated analyses (e.g., tissue samples, body condition, gut analyses, etc.). Similarly, residents could be trained to carry out other sampling for zooplankton and/or relatively simple physical oceanographic measurements to help deduce the seasonally-varying ecosystem in Kuskokwim Bay. This approach would provide a cost-effective description of seasonal variations in the growth and ecology of these animals and their environment. Such efforts would empower local residents with a better understanding of the marine habitats and resources upon which they depend.

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IX. DELIVERABLES:

List deliverables resulting from the project, including Semiannual Progress Reports, data sets, database systems, workshop reports, networking meetings, oral or poster presentations, and submission of journal papers. Explain how the project results have been, and will be, disseminated.

Tom Weingartner, Terry Reeve, Seth Danielson, Warren Jones A satellite-tracked drifter perspective of the nearshore Bering Sea: Science and Community Involvement *(Oral presentation at the Alaska Marine Science Symposium, January 2010 in which preliminary information on the project was presented)*

John Dunwoody, Seth Danielson, Thomas Weingartner, Terry Reeve, and Warren Jones, A satellite-tracked drifter perspective of the nearshore Bering Sea: Science and Community Involvement *(poster presentation at the Alaska Marine Science Symposium, January 2011 in which some of the analyses were presented).*

A satellite-tracked drifter perspective of the nearshore Bering Sea: Science and Community Involvement oral presentation by Tom Weingartner in Nome Alaska at the AYKSSI Workshop March 2010.

Semi-annual progress reports include reports covering the period 1/1 – 6-30/08, 7/1 – 12/31/08. 1/1 – 6/30/09; 7/1 – 12/31/09, 1/1 – 6/30/10, 7/1 – 12/31/10.

Project website: http://www.ims.uaf.edu/NPRBdrifters/.

We have also presented educational programs that incorporated elements of the project in the Quinhagak (2008 and 2009) and St. Paul (2011) public schools and presented how the drifter results could be used as an instructional tool to Public School teachers at an NRPB-sponsored educational workshop held in Anchorage in Fall, 2010).

Portions of the data set were used in:

Danielson, S., L. Eisner, T. Weingartner, and K. Aagaard, 2011: Thermal and haline variability over the central Bering Sea shelf: Seasonal and interannual perspectives. *Cont Shelf Res.*, 31: 539-554.

X. PROJECT DATA:

After quality control procedures, we summarized the results in ASCII data files that include the drifter identification number and position and time data at half-hourly intervals. At each time interval we also include the temperature data and the north-south and east-west velocity components. The velocity components are further segregated into the raw data (which includes the tidal motions) and the detided data. The data can also be obtained directly from the PI:

Dr. Thomas Weingartner
Institute of Marine Science
University of Alaska
Fairbanks, AK 99775
907-474-7993 weingart@ims.uaf.edu

Or from the project website: http://www.ims.uaf.edu/NPRBdrifters/

XI. ACKNOWLEDGEMENTS:

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XII. PRESS RELEASE:

The residents of the Quinhagak collaborated on a project with UAF oceanographers in helping to understand the nearshore circulation of the Bering Sea. They did so by deploying 64 satellite-tracked drifters over the summer and fall of 2008 and 2009 offshore of their village. The drifters were deployed in groups of 4 every 10 – 15 days by the residents and schoolchildren of Quinahgak. The results showed two prominent circulation pathways that juvenile salmon may take as they enter the ocean from the Kuskokwim River. The first pathway is southward along the north-south channel leading to Cape Newenham. The second is westward along the Alaskan coast toward Nunivak Island and Etolin Strait. That flow appears to be interrupted in fall, however, with coastal water being deflected offshore to the west-southwest. Many of the drifters moved more than 200 miles offshore and some as far as the Pribilof Islands and the Bering Sea basin. Other drifters moved northward through Etolin Strait with one drifter reaching Norton Sound and St. Lawrence Island. Scientists hypothesize that if juvenile salmon move westward in shallow waters along the coast that they will encounter a poor food supply, whereas if they move southward along Kuskokwim Bay that they will encounter more food.

XIII. APPENDICES:

NONE