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Exchange Between Elson Lagoon and the Nearshore Beaufort Sea and Its Role in the Aggregation of Zooplankton

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Abstract

Mooring data from August-September 2006 show that non-tidal flows through the passages between the barrier islands of Elson lagoon are well correlated with winds from the east and west quadrants. Moreover, mooring data and satellite imagery demonstrate that wind-driven and/or tidal outflows from Elson Lagoon establish fronts that extend seaward from the passages between the barrier islands of the lagoon. These fronts may act to aggregate zooplankton and thereby present opportunities for efficient grazing by sea birds and whales.

Introduction

Scores of Bowhead whales were observed feeding in a localized area within the nearshore region a couple of miles outside of the barrier islands of the Elson Lagoon system (Figure 1) in September, 2005, during NSF-funded fieldwork conducted near Barrow, Alaska (Project title: "Environmental variability, Bowhead whale distributions, and Inupiat subsistence whaling", Carin Ashjian, Lead-PI, Woods Hole). Net tows within the Elson Lagoon system collected large numbers of euphausiids, whereas net tows outside the lagoon system, away from the feeding whales, collected few euphausiids. The observations of whales feeding near the barrier islands and the large numbers of euphausiids within the lagoon system suggest that circulation/exchange between the lagoon and nearshore region act to aggregate zooplankton for efficient grazing by Bowhead whales.

The principal objectives for this project were to measure the currents through passages between the barrier islands of the Elson Lagoon system, relate these current measurements to local wind forcing, and to integrate the wind forcing and current measurements with observations with NSF-funded field observations of the distribution of euphausiids and other zooplankton in the Elson Lagoon system and nearshore Beaufort Sea to describe how this physical forcing aggregates the plankton.

Methods

Identical moorings, each instrumented with an Aanderaa RCM-11 acoustic current meter and a SeaBird SBE-37 microcat CT sensor, were deployed in Eluitkak Pass (71° 21.239'N, 156° 21.151'W, about 5 km southeast of Point Barrow) and in Ekilukruak Entrance (71° 13.315'N, 155° 48.705'W, near the west end of Cooper Island) (Figure 1 and Figure 2). Eliutkak Pass is a relatively deep (~12 m maximum depth) and narrow (~1 km) channel whose axis is oriented north-south. Ekilukruak Entrance is a silled opening to Elson Lagoon that is relatively shallow (< 3 m) and wide (~6.6 km). The Eliutkak Pass (hereafter Barrow) mooring was deployed in ~6 m of water on 19 August 2006 and recovered on 11 September 2006. The Ekilukruak Entrance (hereafter Cooper Island) mooring was deployed in ~2 m of water on 17 August 2006 and recovered on 15 September 2006. The RCM-11s measured currents about 82 cm above the bottom. The microcats measured temperature and salinity about 65 cm above the bottom. The sample interval for the current meters and microcats was 1 hour.

National Science Foundation funded Onset/HOBO water level recorders were deployed in ~1 m of water in Elson Lagoon near Barrow at 71° 21.357’N, 156° 32.141’W on 8 August 2006 and near Cooper Island at 71° 14.057’N, 155° 42.816’W on 5 August 2006. The Barrow water level recorder was recovered on 12 September 2006 and the Cooper Island recorder was recovered on 15 September 2006. The sampling interval for the water level recorders was 15 minutes.

Wind speed and direction at Barrow during August and September 2006 were obtained from the Atmospheric Radiation Measurement (ARM) website. The sampling interval for the wind data was 6 minutes. This data set was sub-sampled to provide a working data set of hourly measurements.

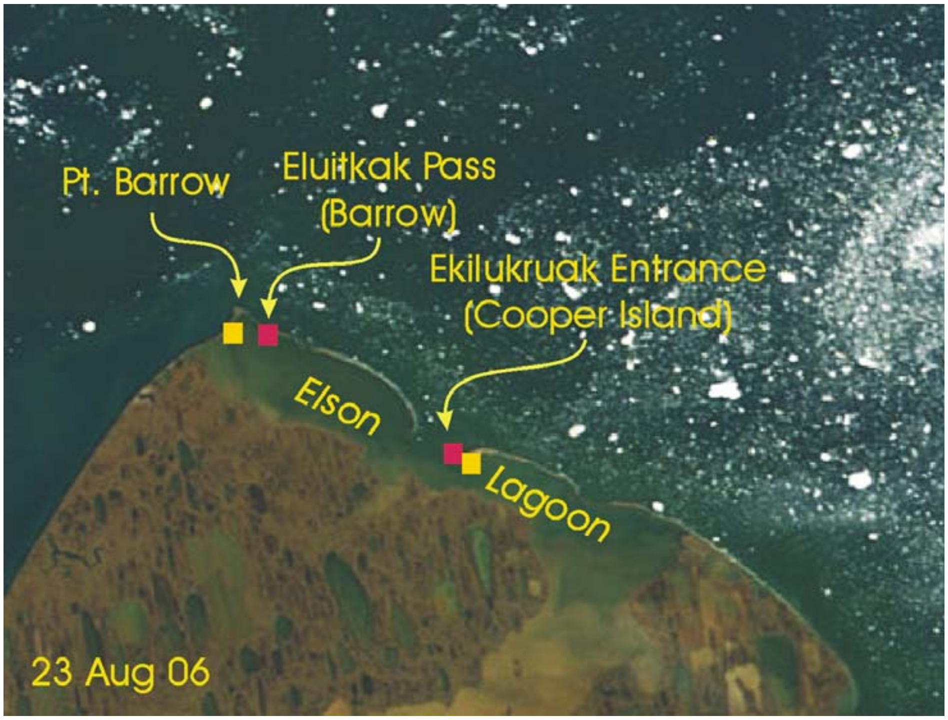

Figure 1 *The Barrow study area including the Elson Lagoon system. The red boxes indicate mooring locations. The yellow boxes indicate water level recorder locations. MODIS image provided by NASA/GSFC.*

Figure 2 *Eluitkak Pass (Barrow) current meter mooring on the afterdeck of the R/V Annika Marie after recovery.*

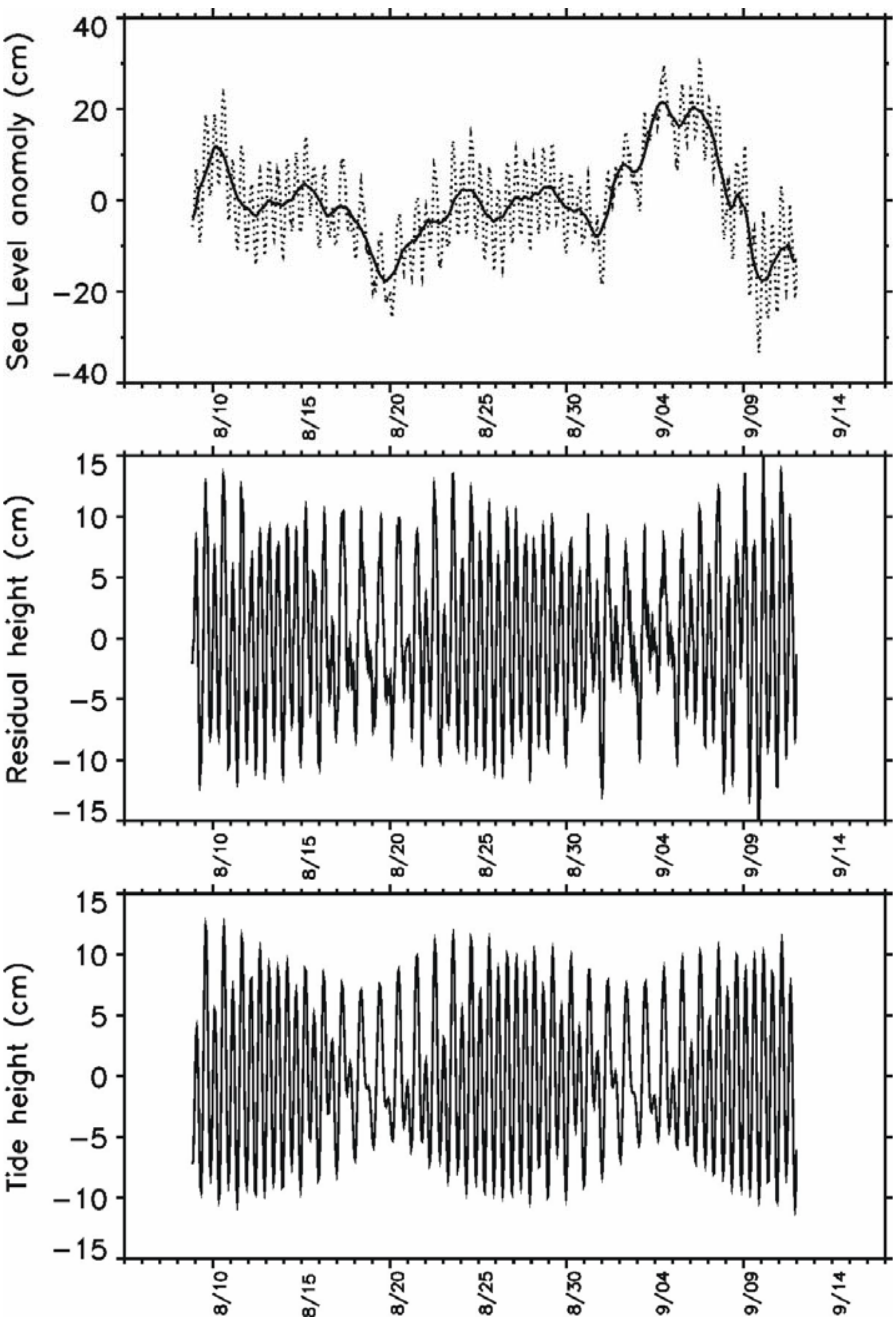

Figure 3 *Elson Lagoon (Barrow site) water level data. (Top) Time series of raw data (dotted line); after smoothing with 25-hour boxcar (solid), (Middle) Time series of residual water level (raw data minus smoothed data), (Bottom) Time series of M2, S2, N2, O1, K1, and P1 harmonics from least squares fit to residual water level time series.*

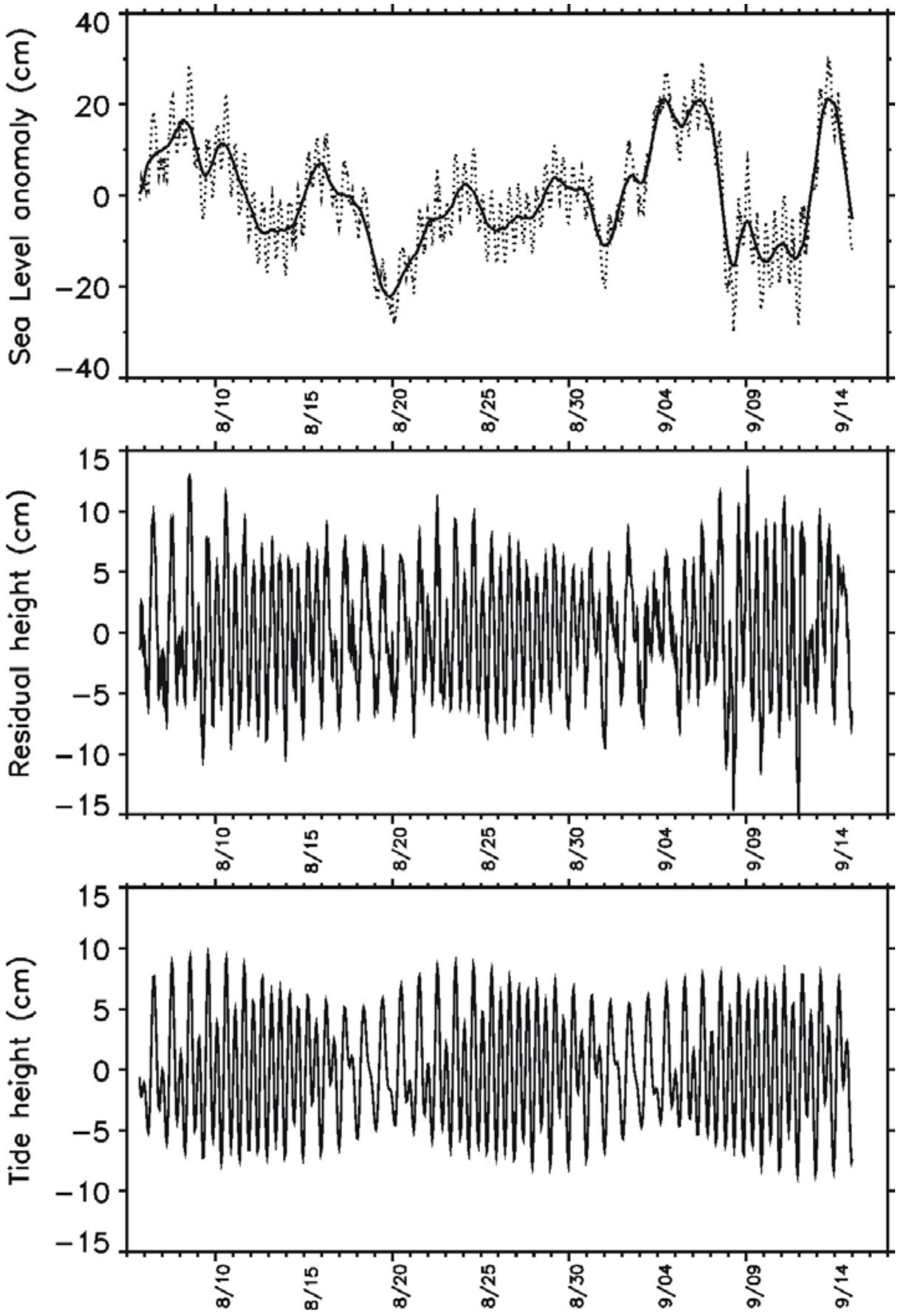

Figure 4 *Elson Lagoon (Cooper Island location) water level data. (Top) Time series of raw data (dotted line); after smoothing with 25-hour boxcar (solid), (Middle) Time series of residual water level (raw data minus smoothed data), (Bottom) Time series of M2, S2, N2, O1, K1, and P1 harmonics from least squares fit to residual water level time series.*

Results

HOBO water level recorders were deployed in shallow protected areas near Barrow and Cooper Island. Water level time series data at these locations are shown in Figures 3 and 4. The raw sea level time series (top panels) clearly show a predominantly semidiurnal tidal signal with a range of about +/- 10 cm that is superimposed on a quasi-weekly signal with a range of about +/- 20 cm. Within the limits of the 15-minute sampling period, changes in tidal heights at Barrow and Cooper Island occur coincidentally. Comparison of Figures 3, top panel and 4, top panel show that low-frequency changes in sea level at Barrow and Cooper Island are roughly coherent.

The principal semidiurnal (M2, S2, N2) and diurnal (K1, O1, P1) tidal constituents of sea level variability were estimated by applying a least squares procedure to the time series of residual sea level (raw sea level minus smoothed sea level; middle panel, Figures 3 and 4) at each location. The resulting time series of estimated tide-driven sea level are shown in the bottom panels of Figures 3 and 4. The amplitudes and phases for the respective tidal components are given in Table 1.

Tidal constituent	Barrow		Cooper Island	
	Amplitude (cm)	Phase (degrees)	Amplitude (cm)	Phase (degrees)
M2 (12.42 hours)	6.0	175	4.2	171
S2 (12.00 hours)	3.4	102	2.7	95
N2 (12.66 hours)	3.4	102	2.7	95
K1 (23.93 hours)	3.3	174	2.4	-177
O1 (25.82 hours)	2.4	27	1.8	40
P1 (24.07 hours)	1.5	-116	1.1	-142

Table 1 Amplitudes and phases (relative to 1 August 2006, 0000h ADT) of tidal height constituents.

Table 1 shows that the semidiurnal tide is greater than the diurnal tide. That tidal heights within the lagoon near Barrow are slightly larger than at Cooper Island may be attributable to a funneling of the tidal wave due to the Barrow recorder being more distant from a lagoon entrance than the Cooper Island recorder. The time series of predicted tide heights at Barrow and Cooper Island both exhibit a ~14-day modulation of the semidiurnal and diurnal components. Tidal heights exhibit predominantly semidiurnal variations centered on 12 August, 26 August and 9 September. Tidal heights exhibit predominantly diurnal variations centered on 19 August and 2 September. The ~14-day modulations (beats) result from the superposition of the M2 and S2 tidal components (beats every 14.79 days) and from the superposition of the K1 and O1 tidal components (beats every 13.62 days).

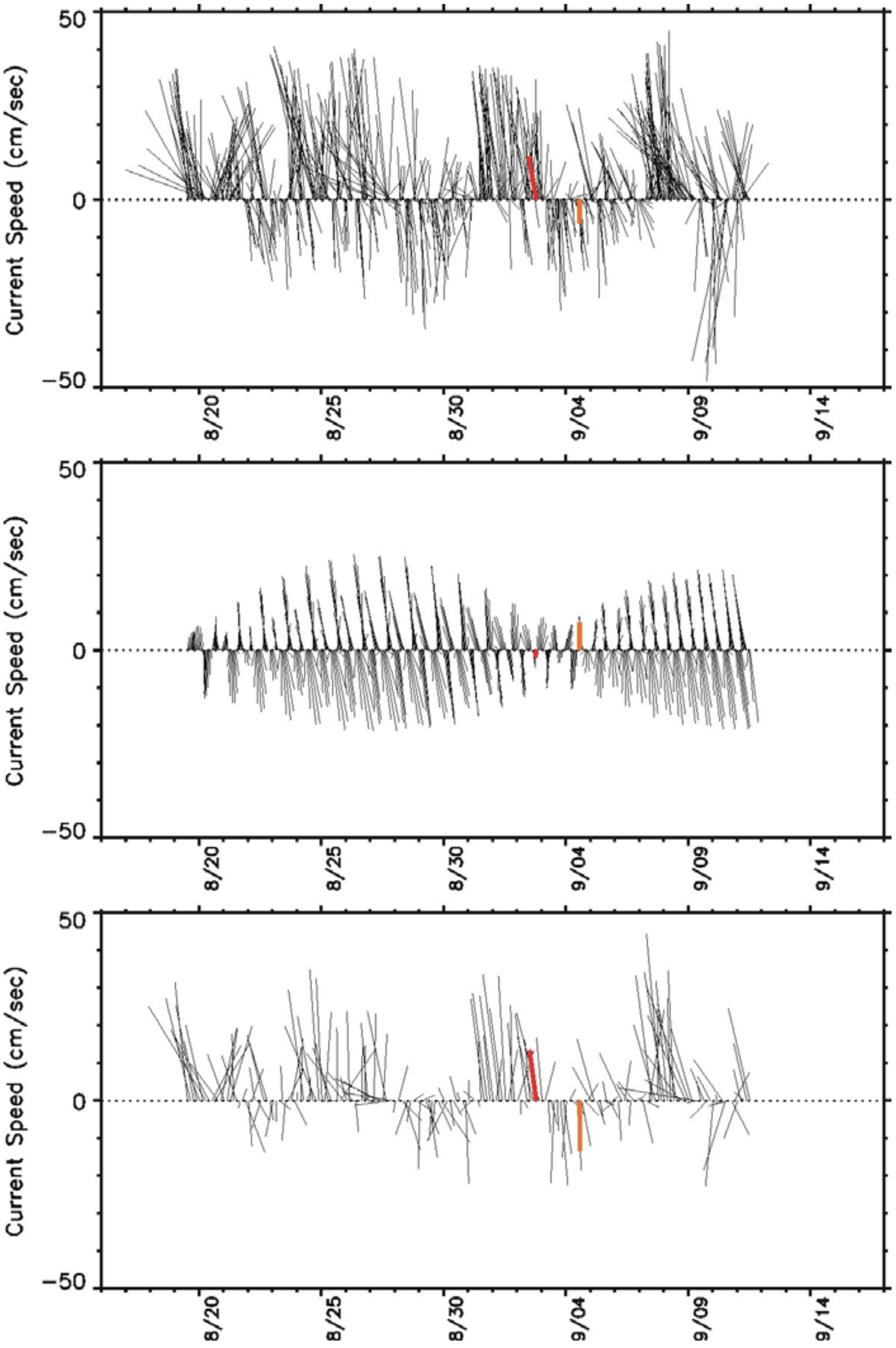

Figure 5 *Time series stick plots of currents at the Barrow mooring location. Sticks pointing up indicate flow to the north (out of the lagoon). (Top Panel) Time series of raw currents. (Middle panel) Time series of tidal currents derived from a least squares fit to M2, S2, N2, O1, K1, and P1 harmonics. (Bottom panel) Time series of non-tidal currents (raw currents minus tidal currents). The red sticks indicate currents at time of the SAR image (see Figure 12) and the orange sticks indicate currents at time of the MODIS image (see Figure 13).*

The stick plot time series of currents at the Barrow location are shown in Figure 5. The raw time series (top panel) shows currents flow predominantly along a north-south axis, reflecting the constraint imposed on the flow by the north-south orientation of the channel in which the mooring was deployed. Tidal currents derived from a least squares procedure (middle panel) are seen to be predominantly semidiurnal and to exhibit a strong ~14-day modulation (beat). Residual, non-tidal currents (raw currents minus tidal currents) appear to vary quasi-weekly (bottom panel). The mean flow for the deployment period is to the north (out of the lagoon) at 7.2 cm/sec. The summary statistics for the currents are given in Table 2.

Near bottom temperature changes recorded by the Barrow mooring (Figure 6, top panel) generally show small amplitudes (<<1°C) at tidal frequencies although episodic amplitudes of ~1°C occur in late August. The maximum near bottom temperature (~4.5°C) recorded by the Barrow mooring occurs at the beginning of the mooring deployment. Four days later on 23 August, the minimum temperature (~0°C) of the deployment period is recorded. Temperatures generally trend warmer through early September with local maxima occurring on 25 August, 28 August, 1-2 September, and 7-8 September after which temperature falls. Near bottom salinity changes (Figure 6, middle panel) also generally show small amplitudes (<1) at tidal frequencies although episodic semidiurnal variations >6 occur in late August and early September. Near bottom salinity varies, by and large, inversely with temperature. In addition to the absolute salinity minimum on 21 August, local minima occurred on 25 August, 27 August, 2-3 September, and 7-8 September.

Comparison of temperature and salinity changes (Figure 6, top and middle panels) with currents (Figure 5, top panel) indicates that temperature maxima and salinity minima typically occur in association with outflows from the lagoon. Conversely, relatively cooler temperatures and higher salinities occur in association with inflows of shelf water to the lagoon.

Not surprisingly, the pressure time series at the Barrow mooring location (Figure 6, bottom panel) and the water level time series recorded ~7 km to the west (Figure 3, top panel) are seen to be very nearly coherent at both tidal and subtidal frequencies.

The stick plot time series of currents at the Cooper Island location are shown in Figure 7. The raw time series (top panel) shows currents flow predominantly along a northwest-southeast axis reflecting the constraints imposed on the flow by shoals flanking the mooring. Tidal currents derived from a least squares procedure (middle panel) are seen to be predominantly semidiurnal and to exhibit a strong ~14-day modulation (beat). Similar to residual currents near Barrow, residual, non-tidal currents near Cooper Island (bottom panel) also appear to vary quasi-weekly, although the directions of residual currents at the Cooper Island mooring are more variable than those at the Barrow mooring. Closer comparison of the residual currents near Barrow (Figure 5, bottom panel) with residual currents near Cooper Island (Figure 7, bottom panel) shows that outflows (inflows) near Barrow often occur during inflows (outflows) near Cooper Island. The mean flow for the deployment period is to the west (276^{o}T) at 5.5 cm/sec. The summary statistics for the currents are given in Table 2.

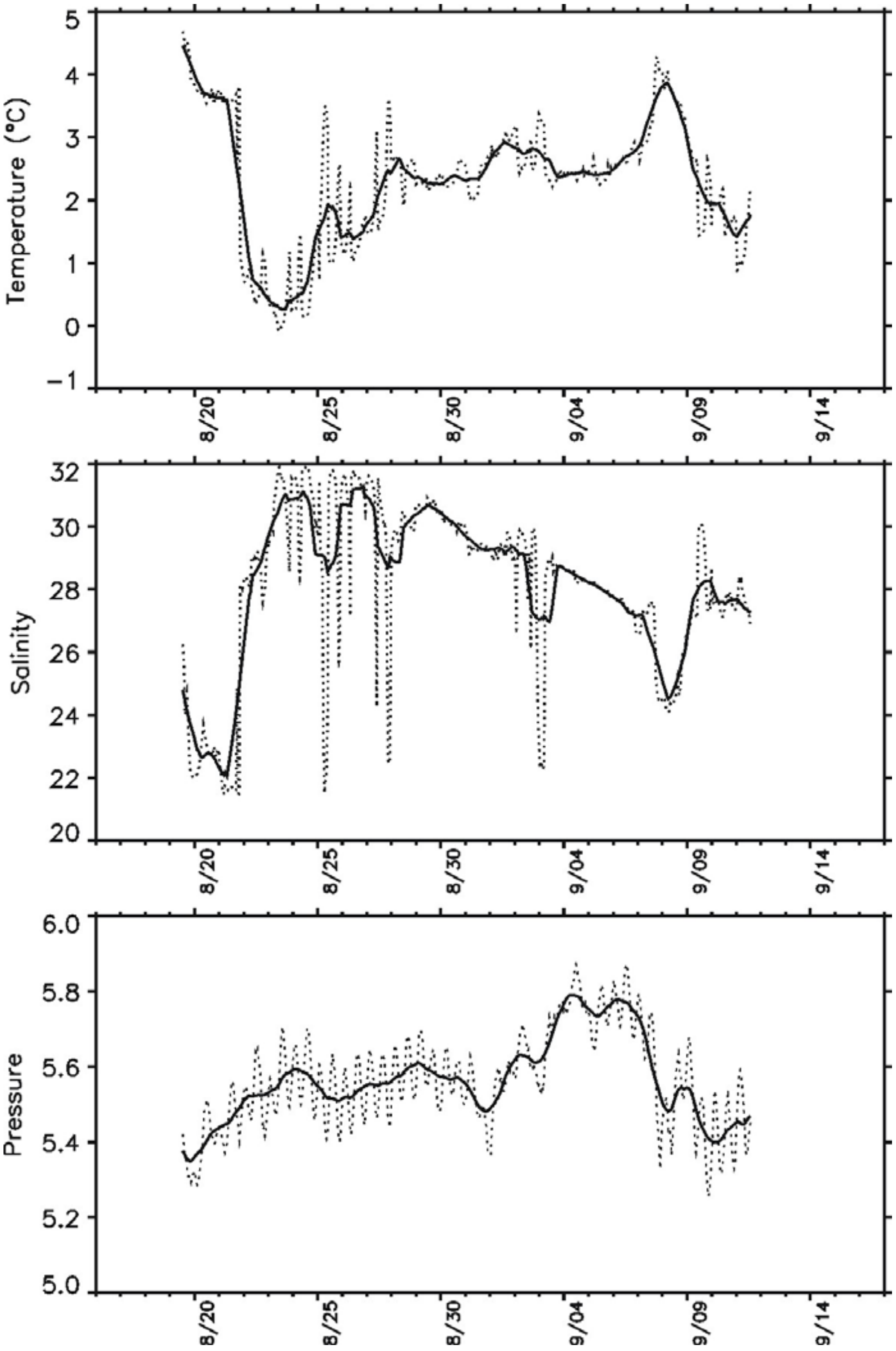

Figure 6 *Seabird SBE37 microcat time series of temperature (top), salinity (middle), and pressure (bottom) at the Barrow mooring location. Dotted lines indicate raw data and solid lines indicate smoothed (25-hour boxcar) data.*

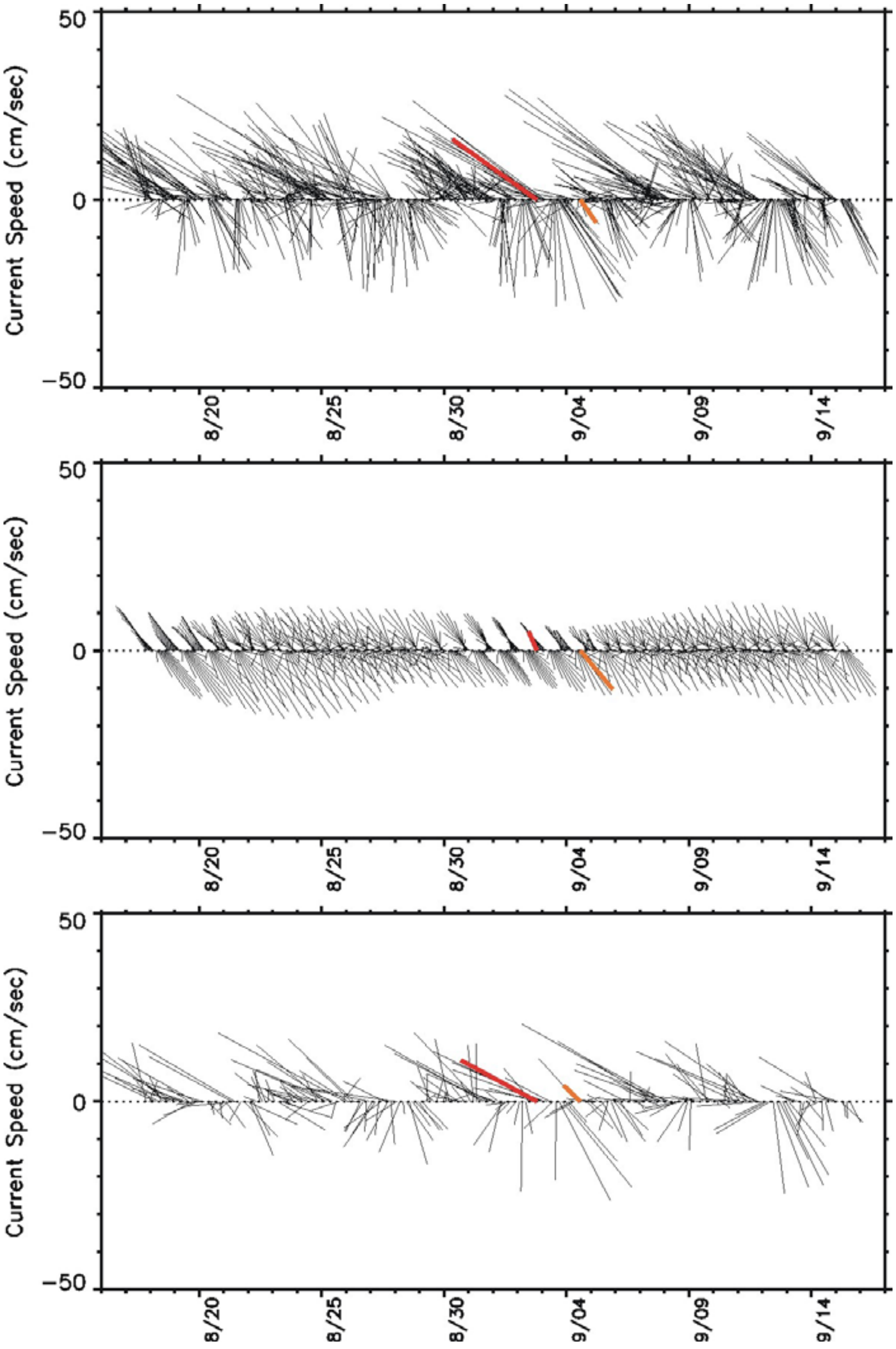

Figure 7 *Time series stick plots of currents at the Cooper Island mooring location. Sticks pointing up indicate flow to the north. Sticks pointing NNW to E indicate flow out of the lagoon. (Top Panel) Time series of raw currents. (Middle panel) Time series of tidal currents derived from a least squares fit to M2, S2, N2, O1, K1, and P1 harmonics. (Bottom panel) Non-tidal, residual currents (raw currents minus tidal currents). The red sticks indicate currents at time of the SAR image (see Figure 12) and the orange sticks indicate currents at time of the MODIS image (see Figure 13).*

	Net Velocity		Principal Axis of Variance		
	Speed (cm s^{-1})	Direction (°T)	Variance Explained %	Direction (°T)	Max Speed (cm s^{-1})
Eliutkak Pass (Barrow)	7.2	350	95	174 / 354	48
Ekilukruak Entrance (Cooper Is.)	5.5	276	83	137 / 317	52

Table 2 Summary statistics for current meter moorings at Barrow and Cooper Island.

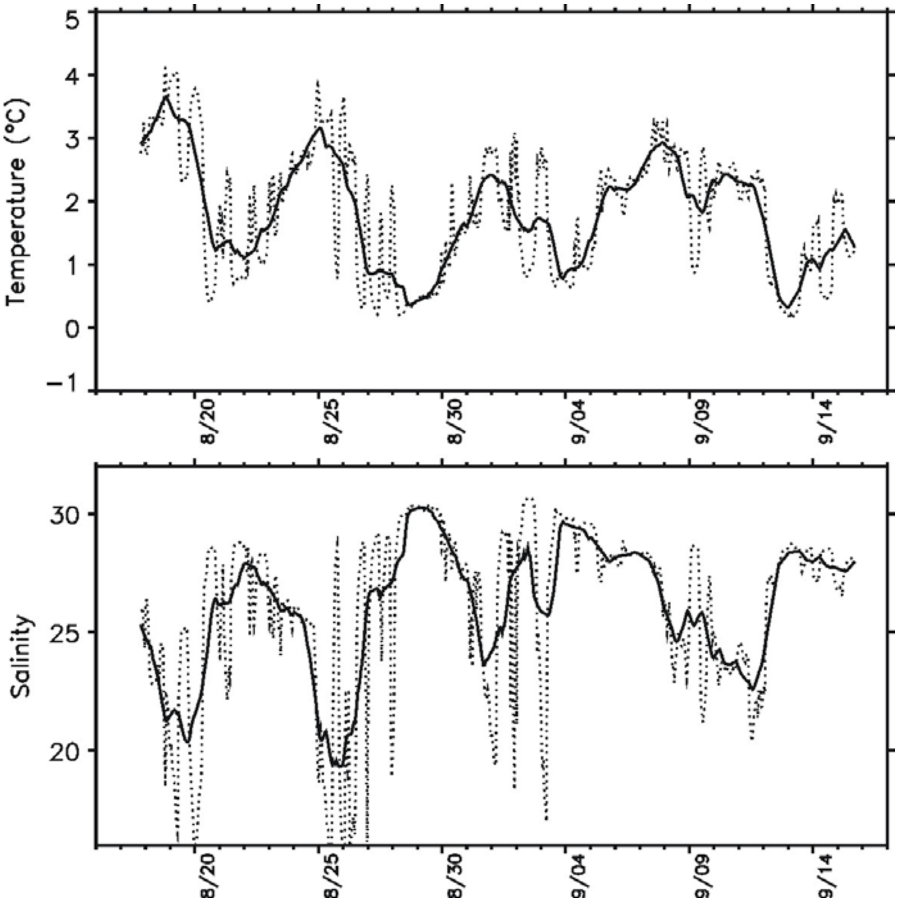

Figure 8 *Seabird SBE37 microcat time series of temperature (top) and salinity (bottom) at the Cooper Island mooring location. Dotted lines indicate raw data and solid lines indicate smoothed (25-hour boxcar) data. The microcat at this location did not have a pressure sensor.*

Near bottom temperatures recorded by the Cooper Island mooring (Figure 8, top panel) show greater tide-related variability than was observed at the Barrow mooring. These tide-related signals are superimposed on a prominent quasi-weekly signal. Near bottom salinity (Figure 6, middle panel) varies, by and large, inversely with temperature. A few of the semidiurnal salinity changes exceed 10 as does the non-tidal salinity signal from 25 August to 28 August.

Comparison of Cooper Island temperature and salinity changes (Figure 8) with currents (Figure 7, top panel) indicates that temperature rises and salinity falls in association with outflows from the lagoon. Conversely, temperature falls and salinity increases in association with inflows of shelf water to the lagoon. The are two likely reasons for greater temperature and salinity changes at the Cooper Island mooring, vis-a-vis Barrow. One is that the Cooper Island mooring was deployed at a much shallower depth (~2 m) than the Barrow mooring (~6 m) and, as such, the Cooper Island instruments sampled the near surface where property gradients tended to be stronger than deeper in the water column. The other is that waters in Elson Lagoon are relatively fresher in the eastern end of the lagoon.

Wind forcing and exchange between Elson Lagoon and the nearshore Beaufort Sea

The relationships between wind forcing and non-tidal exchange between Elson Lagoon and the nearshore Beaufort Sea are depicted in Figures 9 and 10. The combinations of projected winds and currents that are best correlated (r = 0.889) at the Barrow mooring are winds from the east (85°T) and currents to the north (1°T) and winds from the west (265°T) and currents to the south (181°T). Figure 9 (middle panel) indicates that winds from the east (positive wind speeds) promote strong outflows (positive current speeds) from the lagoon whereas winds from the west (negative wind speeds) suppress outflows or promote weak inflows (negative current speeds). In other words, 79% (0.889^2) of the north-south exchange through Eliutkak Pass (Barrow) can be explained by the east-west component of wind velocity. The correlations for all possible combinations of projected wind directions and projected current directions at the Barrow mooring are summarized in the lower panel of Figure 9. Broadly speaking, winds blowing from the eastern quadrant (northeast/southeast) promote outflow from the lagoon through Eliutkak Pass, whereas winds from the western quadrant (southwest/northwest) suppress outflows or promote inflows.

The combinations of projected winds and currents that are best correlated (r = 0.884) at the Cooper Island mooring are winds from the east-southeast (118°T) and currents to the southwest (232°T) and winds from the west-northwest (298°T) and currents to the northeast (52°T). Figure 10 (middle panel) indicates that winds from the east-southeast (positive wind speeds) promote inflows (negative current speeds) to the lagoon whereas winds from the west-northwest (negative wind speeds) suppress inflows or promote weak outflows (positive current speeds). In other words, 78% (0.884^2) of the southwest-northeast exchange through Ekilukruak Entrance (Cooper Island) can be explained by the east-southeast-west-northwest component of wind velocity. The correlations for all possible combinations of projected wind directions and projected current directions at the Cooper Island mooring are summarized in the lower panel of Figure 10. Broadly speaking, winds blowing from the southeastern quadrant (east-northeast/south) promote inflow to the lagoon through Ekilukruak Entrance, whereas winds from the northwestern quadrant (west/north-northeast) suppress inflows or promote outflows.

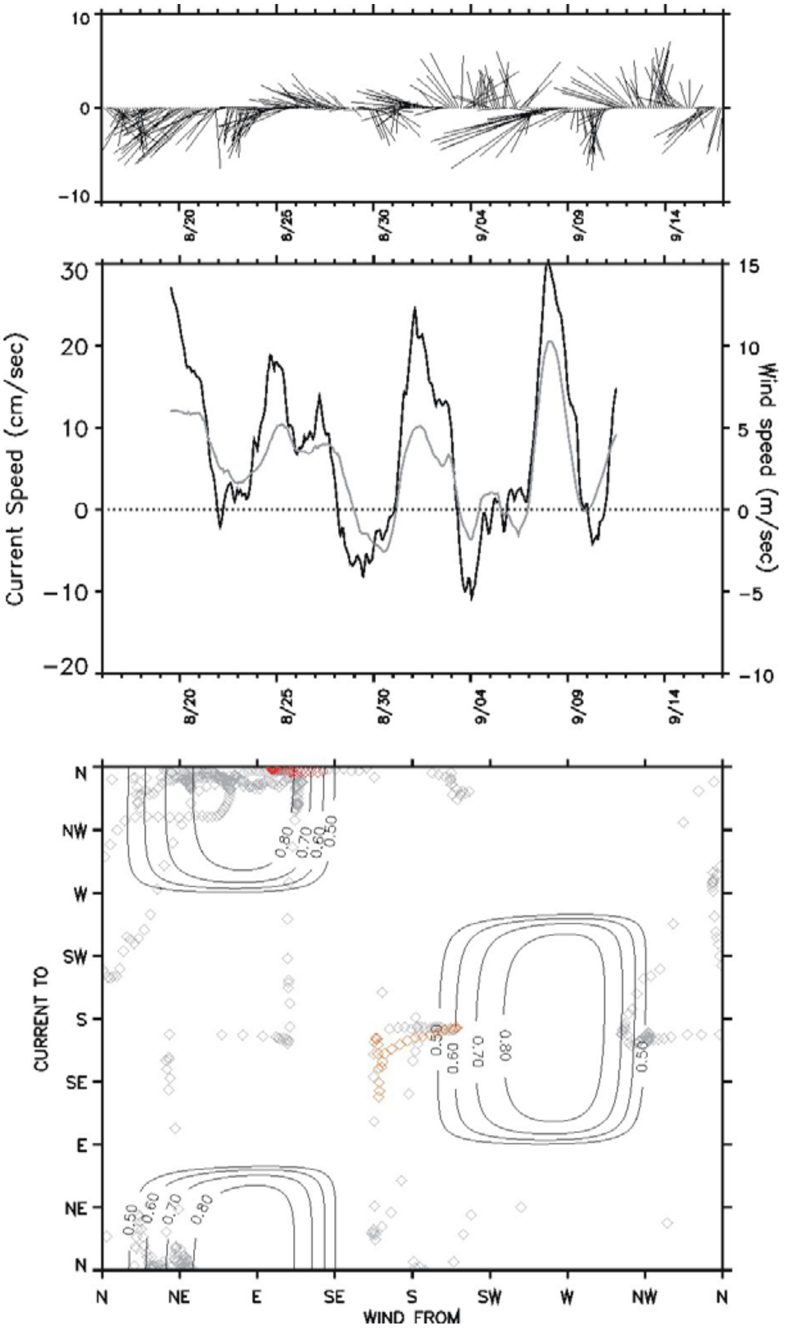

Figure 9 *(Top panel) Time series stick plots of ARM winds at Barrow. Sticks pointing up indicate winds blowing from the south to the north. The wind speed scale is +/- 10 m/sec. (Middle panel) Time series of smoothed (25-hour boxcar) projected (from 85 °T) Barrow wind speed (grey) and smoothed (25-hour boxcar) projected (to 1 °T) Barrow mooring current speed (black). The maximum correlation coefficient, r, is 0.889 at 1 hour lag. (bottom panel) Summary contour plot of correlations between projected wind direction and projected current direction at 0 hour lag. Diamonds indicate actual paired wind-current measurements during the mooring deployment. Red and orange diamonds indicate wind-current measurements on 2 Sept 06 and 4 Sept 06, respectively.*

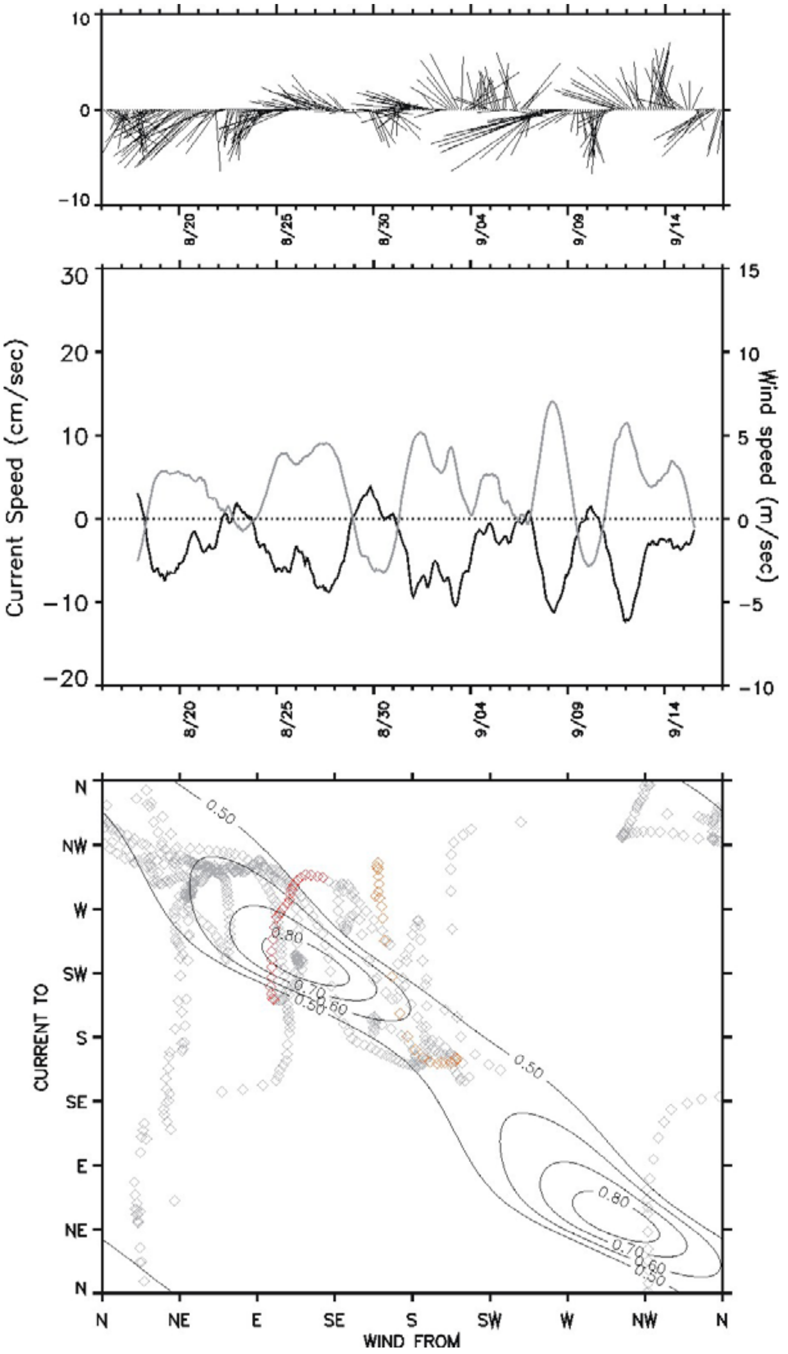

Figure 10 *(Top panel) Time series stick plots of ARM winds at Cooper Island. Sticks pointing up indicate winds blowing from the south to the north. (Middle panel) Time series of smoothed (25-hour boxcar) projected (from 118 °T) Barrow wind speed (grey) and smoothed (25-hour boxcar) projected (to 232 °T) Cooper Island mooring current speed (black). The maximum correlation coefficient, r, is 0.884 at 0 hour lag. (Bottom panel) Summary contour plot of correlations between projected wind direction and projected current direction at 0 hour lag. Diamonds indicate actual paired wind-current measurements during the mooring deployment. Red and orange diamonds indicate wind-current measurements on 2 Sept 06 and 4 Sept 06, respectively.*

Mean winds during the mooring deployments (mid-August to mid-September) were from the east-northeast (67°T) at 2.7 m/sec (5.2 kts) and the principal axis of variance was northeast-southwest (56°T-236°T). As noted above, the mean current directions at the Barrow and Cooper Island moorings were to the north (flow out of the lagoon) and to the west (flow into the lagoon), respectively. These mean wind and mean current relationships are reflected in the correlation matrices depicted in bottom panels of Figures 9 and 10.

Insight to the mechanics of the non-tidal, wind-driven exchange between Elson Lagoon and the nearshore Beaufort sea (inflow at Cooper Island, outflow near Pt. Barrow) can be gained by looking at the relationship of sea level slope between Barrow and Cooper Island (determined from HOBO measurements of sea level at the two locations) and wind forcing. Strictly speaking, absolute sea level slope or sea level difference are not known because absolute sea levels at Barrow and Cooper Island are not known. The best correlation (r = 0.901) between sea level slope and winds occurs for winds from the east-southeast (107°T). Figure 1 shows that the along-shore axis of Elson Lagoon is oriented roughly east-southeast/west-northwest. Figure 11 indicates that winds from the east-southeast (positive speeds) force lagoon waters to the western end of the lagoon, raising sea level (positive sea level difference) near Barrow. Comparison of Figure 11 with non-tidal currents at Barrow (Figure 9, middle panel) and Cooper Island (Figure 10, middle panel) indicates the flow is out of the lagoon near Barrow and into the lagoon near Cooper Island when sea level at Barrow is greater than sea level at Cooper Island. Because Elson Lagoon is semi-enclosed (and the nearshore Beaufort Sea is effectively unbounded offshore), continuity requires outflow at the downwind (downstream) end of the lagoon (near Barrow) and inflow at the upwind (upstream) end of the lagoon.

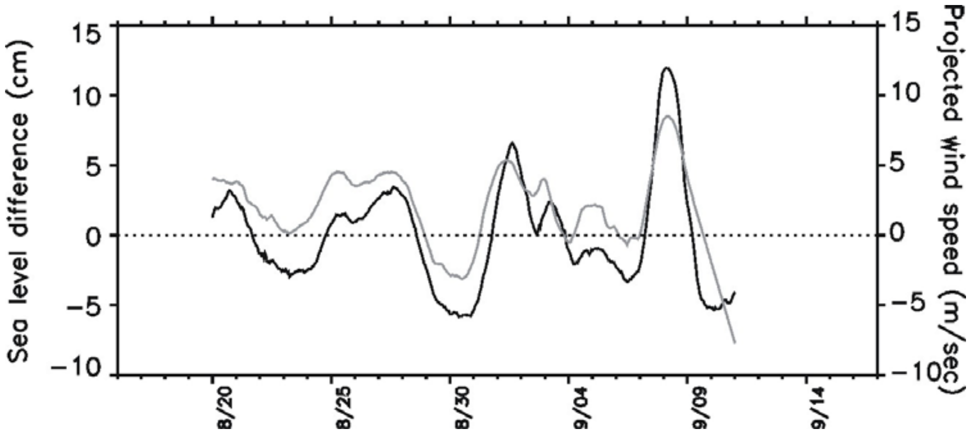

Figure 11 *Time series of sea level difference anomaly (the mean difference is unknown) between Barrow and Cooper Island (black) and projected winds from the east-southeast (grey). Positive sea level differences result when Barrow sea level is higher than Cooper Island sea level.*

Discussion

Aerial surveys of bowhead whales have sometimes observed large groups of whales apparently feeding near the barrier islands of Elson Lagoon. It was hypothesized that these large groups of whales were targeting frontal features because fronts act to aggregate zooplankton prey for more efficient grazing by the whales. The general goal for the 2006 mooring program was to investigate exchange between Elson Lagoon and the nearshore Beaufort Sea to identify the mechanism(s) contributing to the aggregation of zooplankton.

A SAR image of Elson Lagoon and the nearshore Beaufort Sea acquired at 1903 ADT on 2 Sept 2006 (Figure 12) indicates the presence of fronts extending seaward from the passages between the barrier islands of Elson Lagoon. The current meter records from the Barrow and Cooper Island moorings indicate that the flows at both locations were out of the lagoon at the time the SAR image was acquired (see Figures 5 and 7, top panels, red sticks).

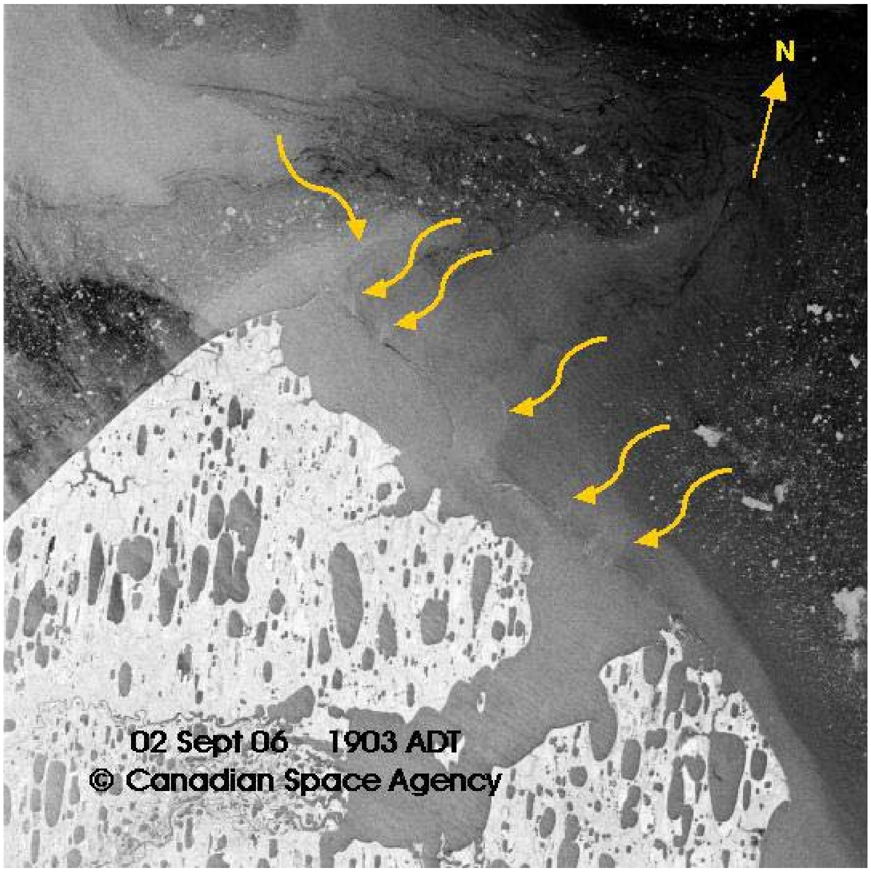

Figure 12 *SAR image of the Elson Lagoon and the nearshore Beaufort Sea. The left-most wavy arrow points to a frontal feature at the shelf break along Barrow Canyon. The other five wavy arrows point to frontal features associated with outflows from Elson Lagoon.*

A MODIS image of Elson Lagoon and the nearshore Beaufort Sea acquired at 1340 ADT on 4 Sept 2006 (Figure 13) shows a small sediment plume extending a very short distance onto the Beaufort shelf near Barrow and no apparent frontal features near Cooper Island or other passes.

The sediment plume near Barrow suggests outflow from the lagoon at this location. At nearly the same time (1338 ADT) as the MODIS image was acquired, thousands of shearwaters, many of which were feeding, were photographed (Figure 13, upper left) adjacent to the sediment plume identified in the MODIS image. The current meter records indicate that the flows at both locations were relatively weak and into the lagoon at the time the MODIS image was acquired (see Figures 5 and 7, top panels, orange sticks). The apparent discrepancy between the MODIS image (suggesting outflow near Barrow) and the current meter record (indicating inflow near Barrow) is likely attributable to estuarine flow through this pass. That is, flow was out of the lagoon at the surface (observed by satellite) and into the lagoon near the bottom (observed by the current meter). CTD casts near the Barrow mooring (not shown) often depicted a highly stratified, two-layer system making it conceivable that flow was out of the lagoon in the surface layer and into the lagoon at depth.

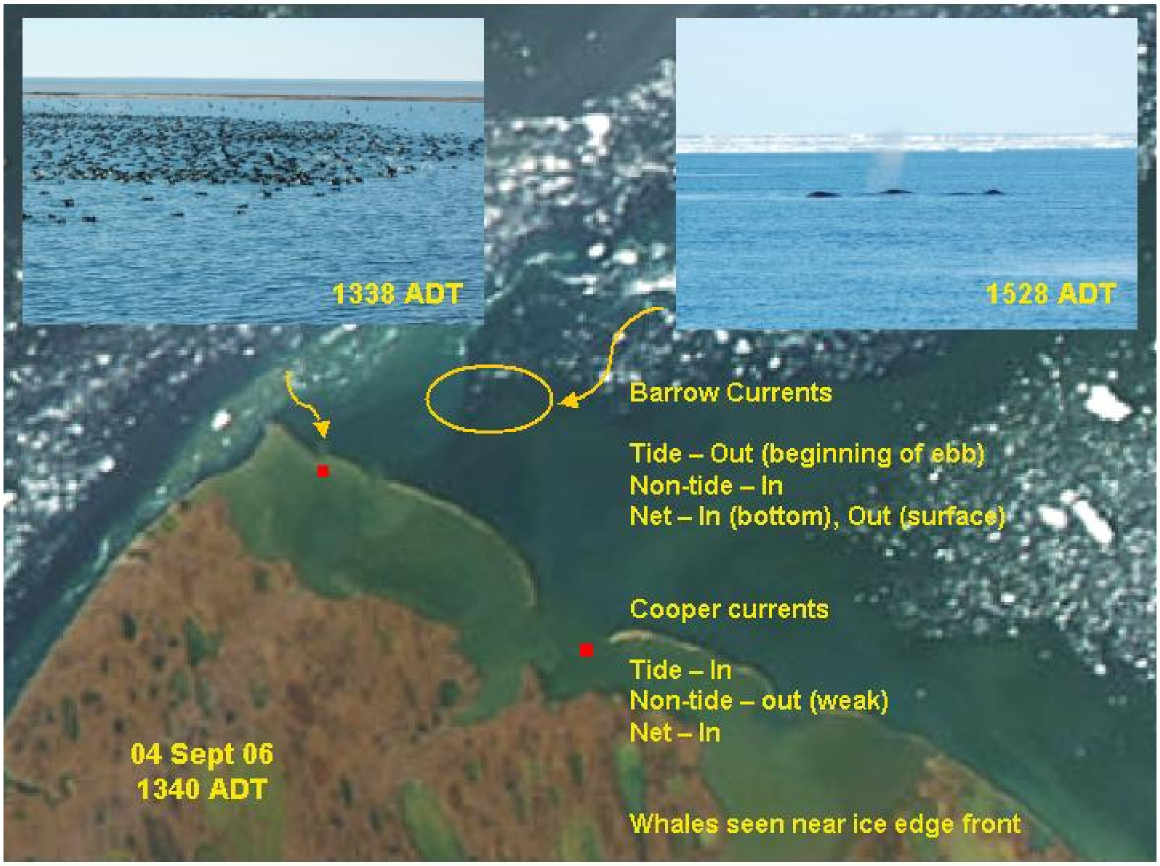

Figure 13 *MODIS-Aqua quasi-true color image of Elson Lagoon and the nearshore Beaufort Sea. Insets: shearwaters near the outflow plume at Eliutkak Pass and bowhead whales near the ice edge.*

List of Project Presentations

Okkonen, S., C. Ashjian, and R. Campbell. Exchange between Elson Lagoon and the Nearshore Beaufort Sea, Alaska Marine Sciences Symposium, 21-24 January, 2007, Anchorage, Alaska.

The Department of the Interior Mission

MARCH 3, 1849

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.