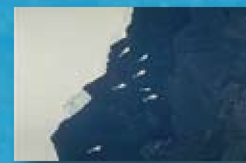
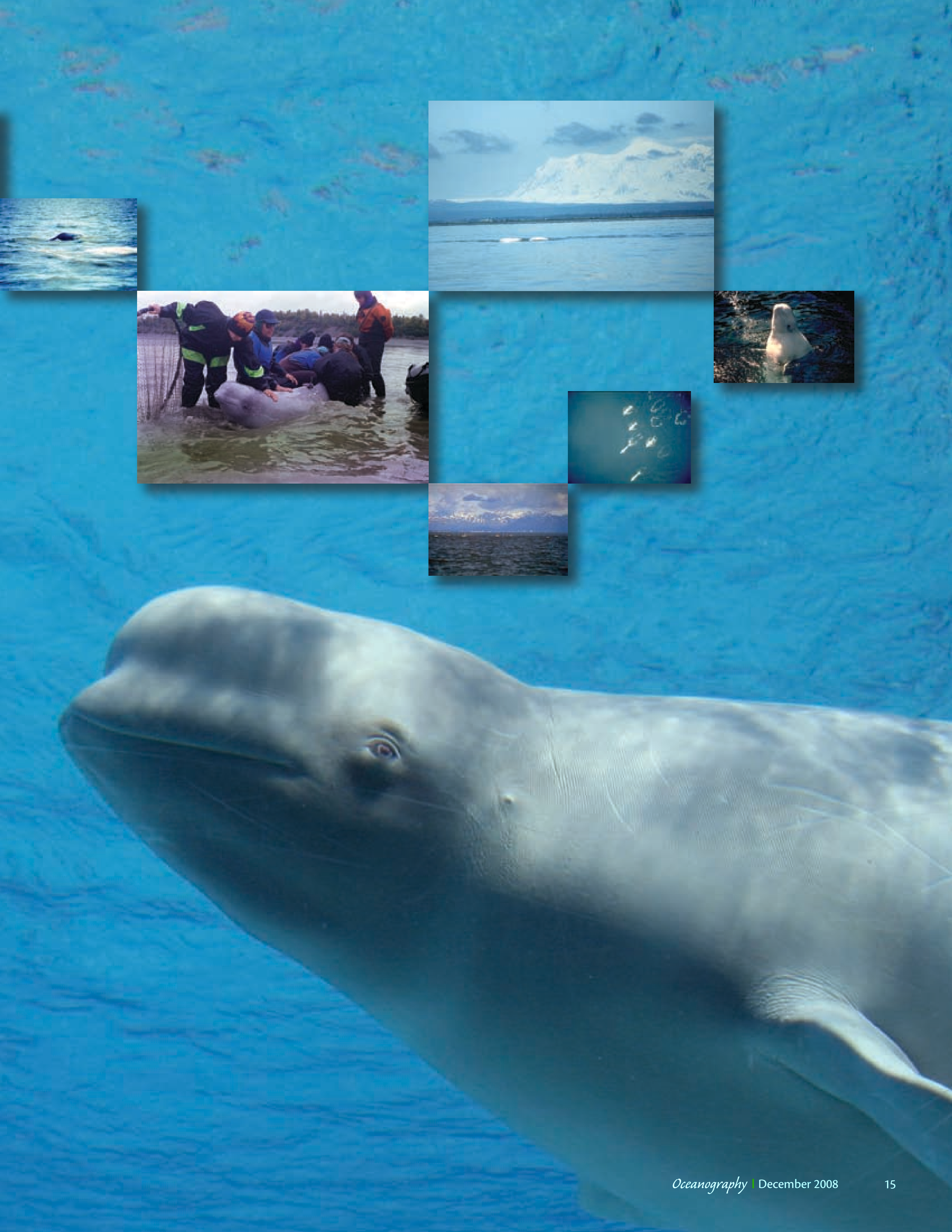
BY TAL EZER, RODERICK HOBBS, AND LIE-YAUW OEY



ON THE Movement OF Beluga Whales IN COOK INLET, ALASKA

Simulations of Tidal and Environmental Impacts Using a Hydrodynamic Inundation Model

ABSTRACT. The population of beluga whales in Cook Inlet, Alaska, is in decline, and since 2000 these whales have been under consideration for designation as "endangered" under the Endangered Species Act. In order to study environmental and hydrodynamic impacts on the belugas' movements and survival in the unique habitat of the inlet, a three-dimensional ocean circulation and inundation model is combined with satellite-tracked beluga whale data. Model-whale data comparisons from two whale paths during a five-day period (September 17–21, 2000) covering 10 tidal cycles suggest that daily movements of belugas in the upper Cook Inlet follow propagation of the tides. Both whales took advantage of the twice-daily flood of mudflats by the very large tides (8–10 m range) to swim toward river mouths in shallow regions that are inaccessible during low tide. A significant correlation was found between whale locations and the model sea level. In the Knik Arm, north of Anchorage, ebbing and flooding rates are predictable, and the tracked whale followed the water velocity in direction and speed. However, in the Turnagain Arm, south of Anchorage, where a large change in topography along the Arm causes nonlinear flooding and ebbing (including strong tidal bore currents with speeds up to 5 m s^{-1}), the movement of the tracked whale was correlated only with the water level, not with the currents. The encouraging results from this study demonstrate the usefulness of the numerical model to help understand the belugas' behavior and will be followed by a more detailed study using a larger tracking data set and longer simulations. Such a study will help to evaluate potential impacts of future changes such as shoreline development, which may change flood regions and the belugas' accessibility to their feeding areas.



INTRODUCTION

Cook Inlet, Alaska, is an Arctic estuary that extends about 250 km from the Gulf of Alaska in the south into the city of Anchorage in the northeast where it branches into two shallower extensions, the Knik Arm north of Anchorage and the Turnagain Arm southeast of Anchorage (Figures 1 and 2). Water levels and currents in Cook Inlet are influenced by tides coming from the Gulf of Alaska; they are significantly amplified as they approach Anchorage (tidal range is ~ 1–2 m near the Gulf of Alaska opening and ~ 8–10 m in the northern part of the inlet; see Figures 2 and 5 in Oey et al., 2007). In Cook Inlet, the tides are predominantly semidiurnal, with a tidal form factor F = (K1+O1)/(M2+S2) = 0.24. The large tides produce strong currents and tidal bores (especially in the Turnagain Arm) with speeds of up to 5 m s^{-1}. The large tides expose extensive mud flats throughout the upper inlet twice daily during the ebb period. The mud flats are visible from satellite images (Figure 2). In addition to tidal currents, buoyancy-driven flows from melting ice, and rivers and winds constitute important components of the circulation and mixing in Cook Inlet. River freshening as well as tidal and wind mixing result in a partially mixed estuary. These processes have been modeled by Oey et al. (2007) using a newly developed wetting and drying (WAD) algorithm (Oey, 2005, 2006) implemented in the Princeton Ocean Model (POM). The same model is used here.

One of many environmental concerns in the region is the declining population of beluga whales, from over 1000 individuals in the 1970s to some 300–400 today (Hobbs et al., 2000, 2005, 2008). In 2000, the Cook Inlet beluga stock was determined to be depleted under the US Marine Mammal Protection Act, and this population is currently being considered for designation as "endangered" under the Endangered Species Act. Aerial surveys indicate that these whales use the flooded tidal flat areas and river mouths made accessible by tidal flooding and that their movements are associated with tidal direction and currents (Rugh et al., 2000, 2004, 2005). These whales are also known to feed heavily on anadromous fish runs that move through these tidal areas. Although the belugas have been observed moving into the upper shallow arms during high tides and departing during

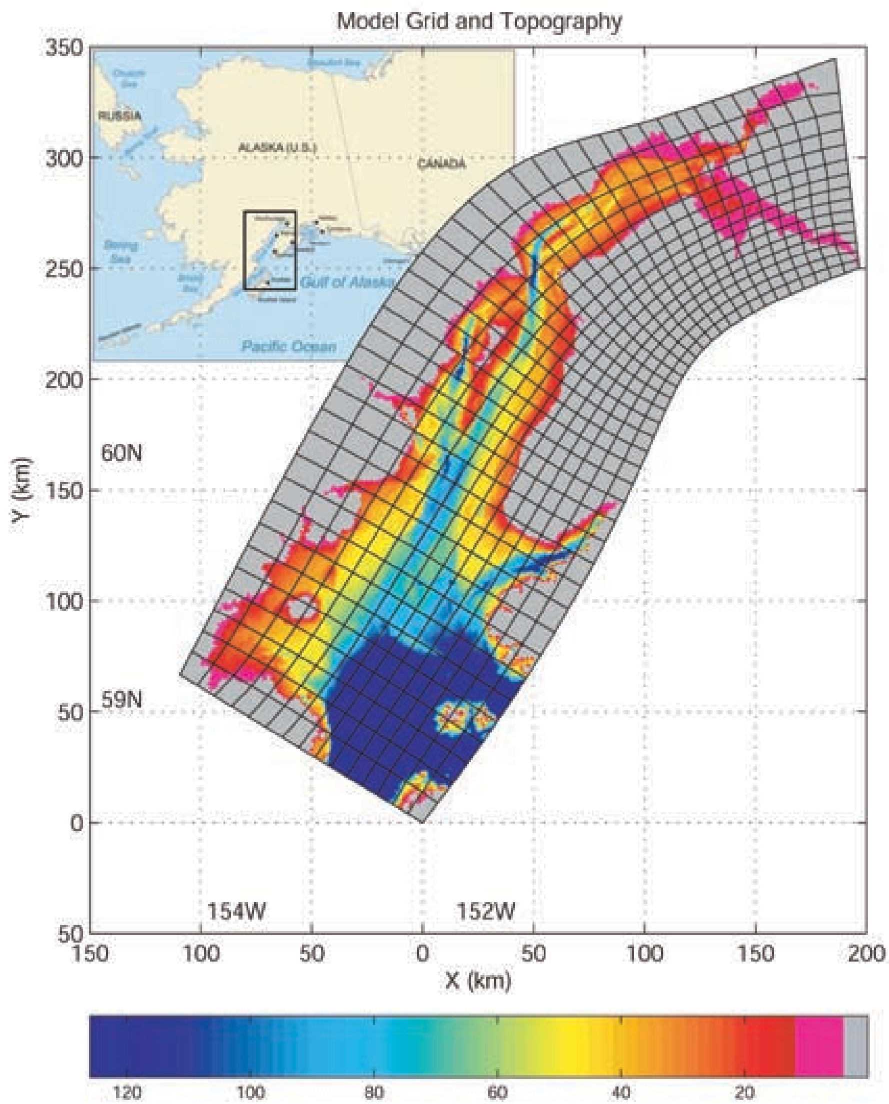


Figure 1. Curvilinear model grid (every tenth grid point is plotted) and bottom topography (depth in m relative to model maximum sea level). Gray represents the absolute land area that is never flooded in the model and magenta represents wetting and drying regions that can be either water covered or exposed land cells in the model. The inset shows a map of the Gulf of Alaska and the study area (indicated by the box).

ebbs (Hobbs et al., 2005), it has not been possible to quantitatively correlate their movements with physical parameters such as water depth, tidal currents, and salinity fronts (shallow mudflats are inaccessible to boats and have dangerously strong currents, precluding direct data gathering). Variations in these water properties may affect the abundance and distribution of the fish on which the belugas prey, and thus influence the belugas' movements (Hobbs et al., 2005).

US National Oceanic and Atmospheric Administration (NOAA) scientists used satellite telemetry (System ARGOS; Figure 3) to track the belugas' movements over several months during late summer through mid spring for three years (Hobbs et al., 2005). The tracking shows a clear seasonal movement of the population that depends on ice coverage and feeding locations, as well as a daily excursion of up to 30 km per day in the upper inlet (mostly during summer when the area is ice free). The daily excursions of the belugas are comparable to the tidal excursion, which is proportional to the excursion of the salinity front (Figure 4) and the size of mudflat exposed at low tide (Figure 2) in the upper inlet. In this article, we describe a new and creative way to analyze these tracking data using a three-dimensional numerical model of Cook Inlet (Oey et al., 2007; Figure 1). This model is used to simulate the missing physical data over the shallow upper inlet to test the hypothesis that the belugas' daily movements are being controlled by tidal-driven dynamics. The results presented here are the proof of concept for this new approach.

Because the belugas' habitat is adjacent to the City of Anchorage as well as two large military bases and areas of increasing development, changes in the shoreline may affect tidal flux and the movements of prey used by the belugas. Thus, understanding and modeling the

Tal Ezer *(tezer@odu.edu) is Associate Professor, Center for Coastal Physical Oceanography and Virginia Modeling, Analysis and Simulation Center, Old Dominion University, Norfolk, VA, USA.* **Roderick Hobbs** *is Research Scientist, National Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA/Fisheries, Seattle, WA, USA.* **Lie-Yauw Oey** *is Research Scholar, Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA.*

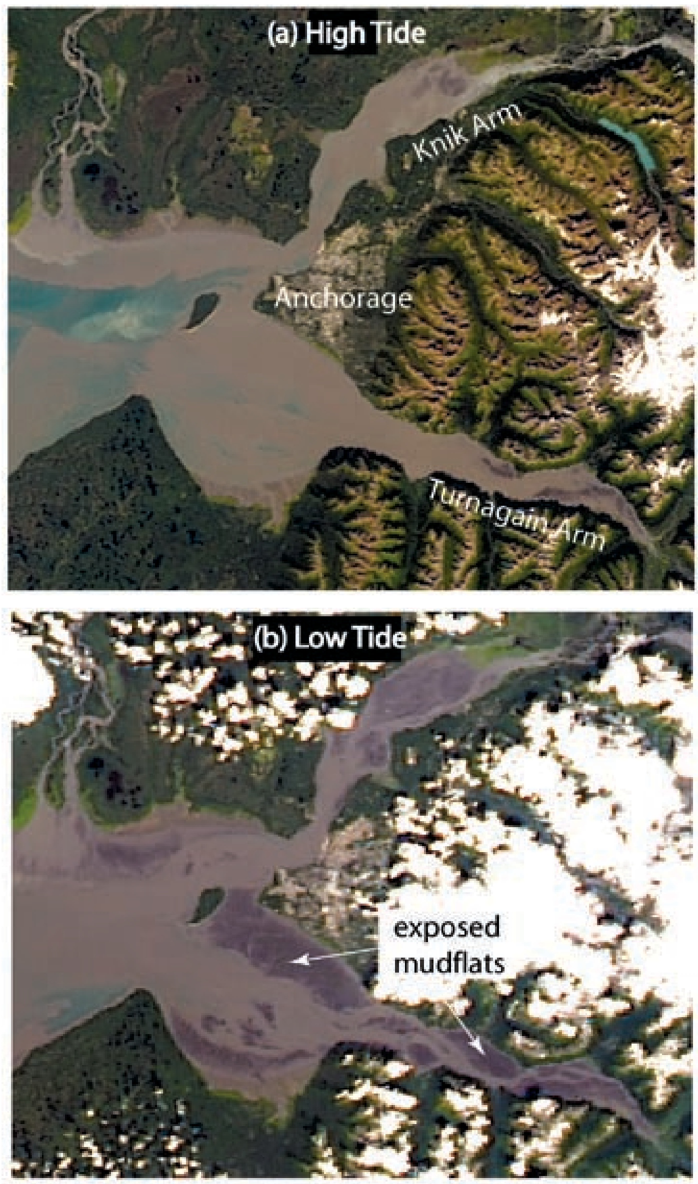


Figure 2. Examples of MODIS true-color images in the upper Cook Inlet: (a) during high tide (August 27, 2005, at 2105 GMT), and (b) during low tide (July 22, 2005, at 2315 GMT). The darker areas in (b) are exposed mudflats at low tide.

Figure 3. Tagging a beluga whale in Cook Inlet with a satellite telemetry system.

whales' movements in relation to the tidal flux and other physical parameters will allow estimation of the impact of potential changes in the tidal and shoreline areas on the beluga population. The model also has the potential to be an important tool to help monitor the inlet and play a role in predicting the impact of climate change, shoreline development, pollution, and oil spills.

NUMERICAL MODEL AND BELUGA WHALE DATA

The details of the Cook Inlet model are given in Oey et al. (2007) and the wetting and drying scheme in Oey (2005, 2006), so the model is only briefly described here. The model uses a curvilinear-orthogonal horizontal grid with 401 x 151 grid points; grid sizes vary from ~1 km near the southern open boundaries of the model domain to less than 0.5 km in the north near Anchorage and in the Knik and Turnagain Arms (Figure 1). The vertical grid uses 16 terrain-following ("sigma") levels. Note that there are no detailed topographical maps of the mud flats seen in Figure 2b, and the model does not resolve the various narrow channels there (some only a few meters wide). Thus, the model topography is roughly represented by one wide channel in the innermost part of the inlet. Forcing data include hourly surface wind fields derived from four local NOAA weather stations, and US Geological Survey data provide monthly runoffs of the seven largest rivers plus other tributaries (see Oey et al., 2007, for more details of the data and the locations of stations and rivers). Climatological temperature and salinity data were used for initial conditions. Tidal forcing is imposed at the entrance to Cook Inlet on the model's south boundary. Oey et al. (2007) performed various sensitivity studies that show, for example, that simulations with or without winds are very similar, because the currents, sea level, and salinity fronts are driven in the model mainly by tidal forcing and river runoffs. In the results presented here, only variations within a tidal cycle are analyzed (not variations from day to day or season to season), so the model here is forced only by mean wind and river data representing typical, ice-free summer to early fall conditions.

The three-dimensional model simulates temperature, salinity, currents, sea level, mixing parameters, and land exposure. Of particular importance for this study is the dynamics in the two shallow arms; Figure 4 shows the salinity and sea level along the Turnagain and Knik Arms during low- and high-tide stages. Note that the end portion of the Turnagain Arm is relatively flat, so that it is not completely dry during ebb when the flood at the lower end has already begun. The appearance of a "tidal bore" can be seen in the model (at 50 km in Figure 4b); velocities reach ~ 5 m s^{-1} near the surface front. In the Knik Arm, on the other hand, the bottom slope allows draining of fresh water from the shallow end all the way to the deeper area during ebb, and sea level is relatively flat with more linear dynamics. The range of belugas found is also shown in Figure 4, indicating that the belugas are indeed moving up the inlet (toward the right) during high tide (Figure 4b and 4d) and down the inlet during low tide (Figure 4a and 4c), as observed previously; more discussion on the beluga data analysis follows.

The beluga tag data are described in Hobbs et al. (2005). These data provide the locations of whales at variable intervals from minutes up to a day. Tag data for two whales during the period September 17–21, 2000, were analyzed; whale #1 spent the entire period in the Turnagain Arm and was located 40 times, while whale #2 spent this period in the Knik Arm and was located 30 times. Note that detailed analysis of the long-term movement of the belugas with a larger data set covering several years is now underway, but here we aim to first demonstrate that this model-beluga comparison is even feasible. Because here we only look at the dependency of beluga movement on the tidal stage, not the changes from day to day or from season to season, analysis of 10 tidal cycles should provide proof of concept. The data include location information $[X^n(t_i), Y^n(t_i)]$, i = 1,40 for n = 1 (whale #1) and i = 1,30 for n = 2. These data enable us to compare whale movements in different locations at the same time. About two to three points were removed from the data of each whale as they look unrealistic, for example, when a whale was located at two places far away from each other within a few minutes. Because each location data point has a different time and place, and sea level is uneven along the inlet (Figure 4), we chose the sea level at Anchorage as a common reference for defining the tidal stage of each location data point. Each data point was assigned a tidal stage hour between 1 and 12, so, for example, 0h is ebb, 3h is low tide, 6h is flood, and 9h is high tide (independent of the day). This method allowed us to make plots showing all the locations occupied by each whale at a certain phase of the tide, regardless of the tidal cycle during which the data were collected. Because of the irregular location times, some hours had no data and some had three to eight locations for each whale.

To estimate the speeds of the whales, we used consecutive locations:

$U^n(t_i) = [X^n(t_i)-X^n(t_{i-1})]/[t_i-t_{i-1}]$ and

$V^n(t_i) = [Y^n(t_i)-Y^n(t_{i-1})]/[t_i-t_{i-1}]$.

The model velocity at each time and location was also found for comparison, $U^{mod}(X^n,Y^n,t_i)$ and $V^{mod}(X^n,Y^n,t_i)$. The component of the velocity along each arm was calculated from both the whale data and the model simulation; positive values represent motion toward

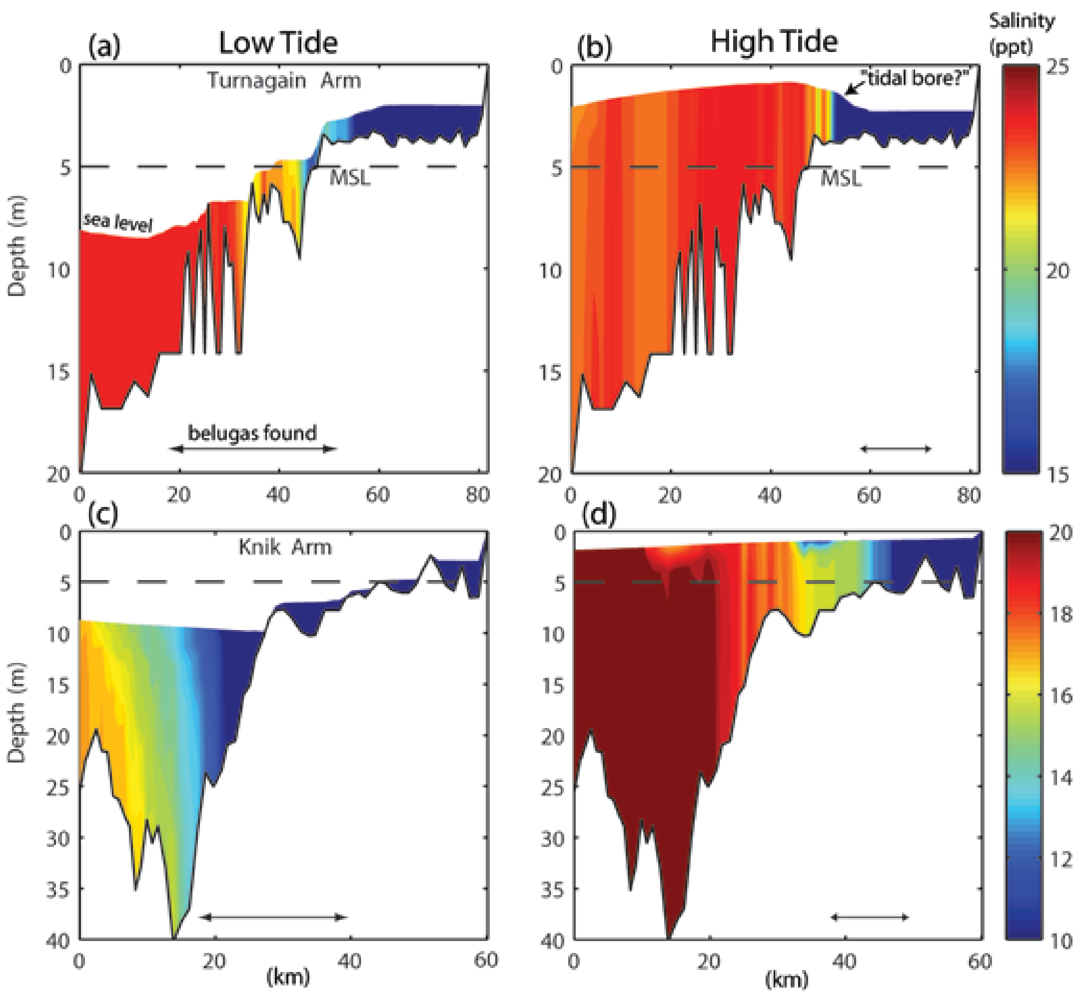


Figure 4. Cross section of salinity (color scale in ppt) during low (left panels) and high (right panels) tides for the Turnagain (upper panels) and Knik (lower panel) Arms, as simulated by the numerical model. The sections are along the deepest part of each arm. Mean sea level (MSL) is indicated by the dashed line. The ranges where belugas were observed in this study are indicated at the bottom of each panel.

shallower regions and vice versa. Because of the uncertainty in the exact locations of the whales and the large variations in time intervals between whale data points, it is difficult to estimate errors, so we are mostly interested in trends and whale swimming directions.

RESULTS

Figure 5 shows examples of whale locations plotted on the model sea level every two hours; a time series of the model sea level in Anchorage is also shown as an inset to indicate the tidal stage. The pattern for the rest of the 12-hours tidal stages (not shown) are similar, though most have fewer spotting points than the hours shown here. During low tide (Figure 5a) the two whales are found in the middle and lower sections of the two arms, but during flood (Figure 5b) they move up the arms to reach their farthest locations during high tide (Figure 5c); the whales begin moving down the arms when the ebb starts (Figure 5d). The whale locations are more clumped together during high tide than low tide (as seen also in Figure 4), indicating that they travel up the arm to the same river every tidal cycle. Note from the satellite images (Figure 2b) that these areas in the upper arms are mostly inaccessible or dangerous to the whales during low tide, as there is then water only in narrow channels or in very shallow pools over the mudflats.

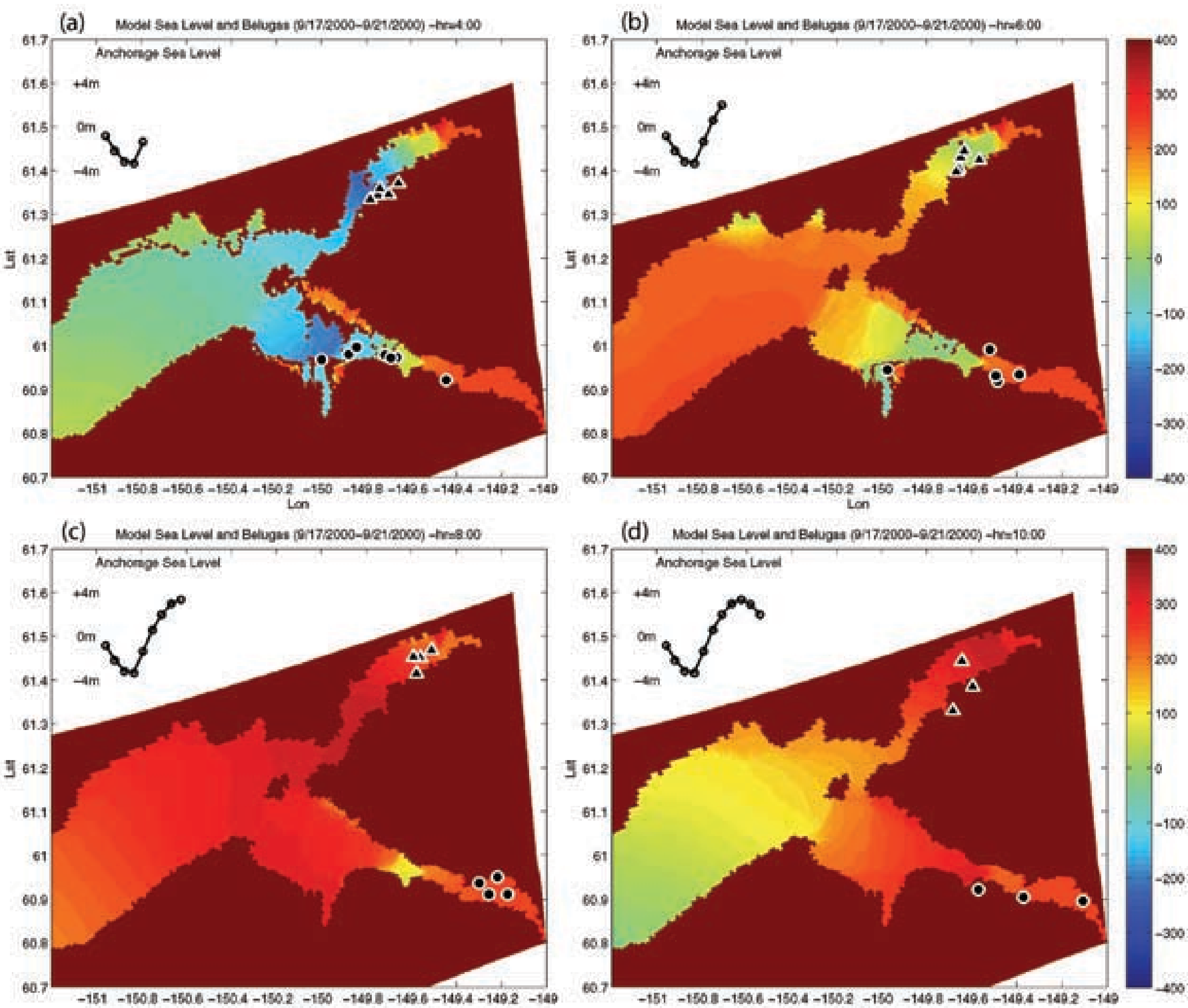


Figure 5. Model sea level (color scale in centimeters relative to MSL) and spotting locations of two belugas between September 17 and 21, 2000. In each hourly tidal stage (indicated by the model sea level in Anchorage shown in the inset), the whale spottings during this period are shown. For example, (a) shows that one hour after low tide, the whale in Knik Arm was located four times (triangles), while the whale in Turnagain Arm was located seven times (circles).

It seems that the whales follow the tides, but can their movements be predicted from observed sea level? Figure 6 indicates that the distance they travel from deep to shallow waters is highly correlated with the sea level record in Anchorage, with linear correlation coefficient R > 0.7 (> 99% confidence level). In each tidal cycle, the whale in the Knik Arm moves about 30 km, while the whale in the (longer) Turnagain Arm moves about 50 km. These distances are consistent with the movements reported by Hobbs et al. (2005). During high tides, the whales are found (for this five-day period) within about a 20-km range, while during low tides they can spread farther over about a 30-km range.

The coupling between the complex topography of the upper Cook Inlet and the very high tide results in a nonlinear relation between sea level and local currents. Figure 7 thus shows the surface water speed and direction in the model and the whales' locations as in Figure 5. The difference in motion between the two whales is quite striking. In the Knik Arm, the whale seems to follow the fast-moving tidal front (the region with large velocity gradients seen in Figure 7a–c, which is just ahead of the salinity front seen in Figure 4c–d). However, in the Turnagain Arm, the whale does not follow the velocity front (Figure 7) or the salinity front (Figure 4); in some cases, it even swims against the currents (Figure 7b–c). More quantitative comparison of water velocity and estimated whale swim speed (Figure 8) shows a better correlation in the Knik Arm (R = 0.52 at 95% confidence level) compared with the Turnagain Arm (R = 0.21 at less than 80% confidence level). Note also that whale #1 in the Turnagain Arm usually moves about twice as fast as the water velocity (Figure 8c), while whale #2 in the Knik Arm moves at about the same speed and in the same direction as the water velocity (Figure 8a). There are strong currents in the Turnagain Arm of up to 5 m s^{-1} associated with the tidal bore (Oey et al., 2007), but the whales seem to swim ahead of the strong currents (e.g., in Figure 7c, the whale is found around 60.9°N, 149.2°W while the tidal front is around 60.95°N, 149.6°W). Because whale #1 needs to swim farther away in the Turnagain Arm than whale #2 in the Knik Arm, the good correlation between the whales' movements and sea level (Figure 6) suggests that the whale in Turnagain Arm swam ahead as soon as the water was deep enough, not waiting for the shallow part to be completely filled (which may take a few hours). The nonlinear nature of the flooding and ebbing in the Turnagain Arm (currents in opposite directions at different places at the same time and unpredictable tidal bores) makes it more difficult for the whale to simply follow the tidal currents, as the whale in the Knik Arm seems to do.

CONCLUSIONS

The subarctic Cook Inlet estuary is a unique environment because of its high-latitude location and its very large tide (8–10-m range) and associated large mudflat regions (tens of square kilometers). The beluga whale population residing in the inlet is isolated from other belugas in the Bering Sea and depends on this environment for survival, in particular, accessibility to feeding areas. It is not clear why the number of belugas has been declining. Therefore, there is considerable interest in studying their behavior

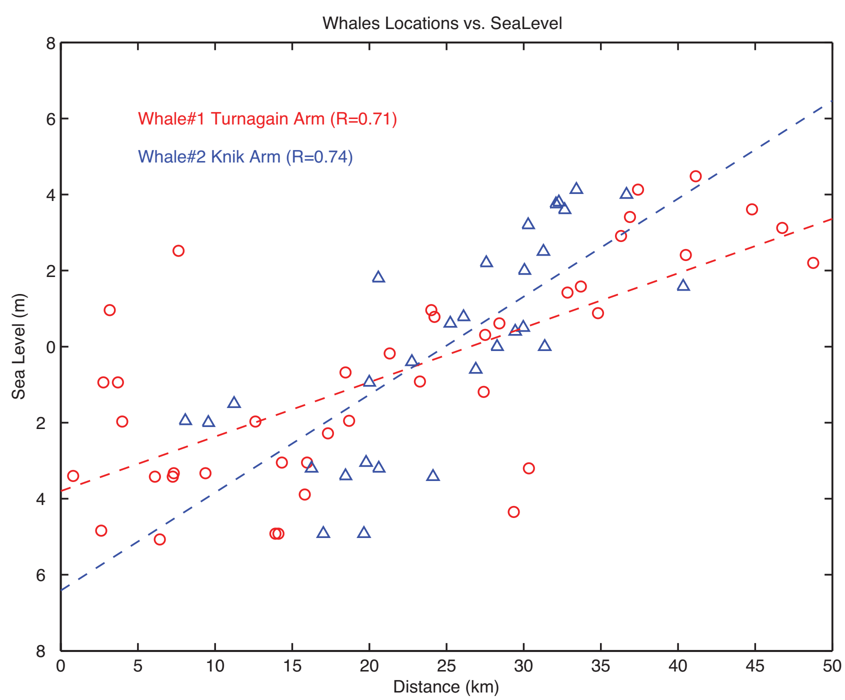


Figure 6. Model sea level at Anchorage versus whale locations (distance relative to a spot near Anchorage). Red circles and blue triangles represent whale #1 in Turnagain Arm and whale #2 in Knik Arm, respectively. Linear best-fit lines for each whale are also shown.

and response to the potential impacts of changes in physical parameters such as temperature, salinity, currents, and ice coverage. In this study, we use an inundation and circulation numerical ocean model to help interpret the belugas' movements as a function of water depth and currents in the environment. In particular, the model provides information on currents and water coverage over shallow mudflats where no direct observations are available. We compare the belugas' movements as tracked by satellite telemetry with physical parameters obtained from the numerical ocean model that includes inundation processes (Oey et al., 2007). The results show significant correlations between belugas' movements in the upper Cook Inlet and the model sea level and currents; the belugas move some 30–50 km each day to follow the tidal cycle and water coverage. However, comparing the simultaneous behavior of two whales during a five-day period reveals differences related to the flow dynamics in Knik and Turnagain Arms. In the Knik Arm, where the tidal dynamics is linear and more predictable due to a relatively even bottom slope, the whale mostly followed the tidal currents. In the Turnagain Arm, where tidal dynamics is nonlinear, with ebbing and flooding occurring at the same time in different parts of the arm and with the existence of tidal bores, whale movement correlated with sea level, but not with local currents. In both cases, the whales take advantage of the large tide to swim to shallow areas that are not accessible

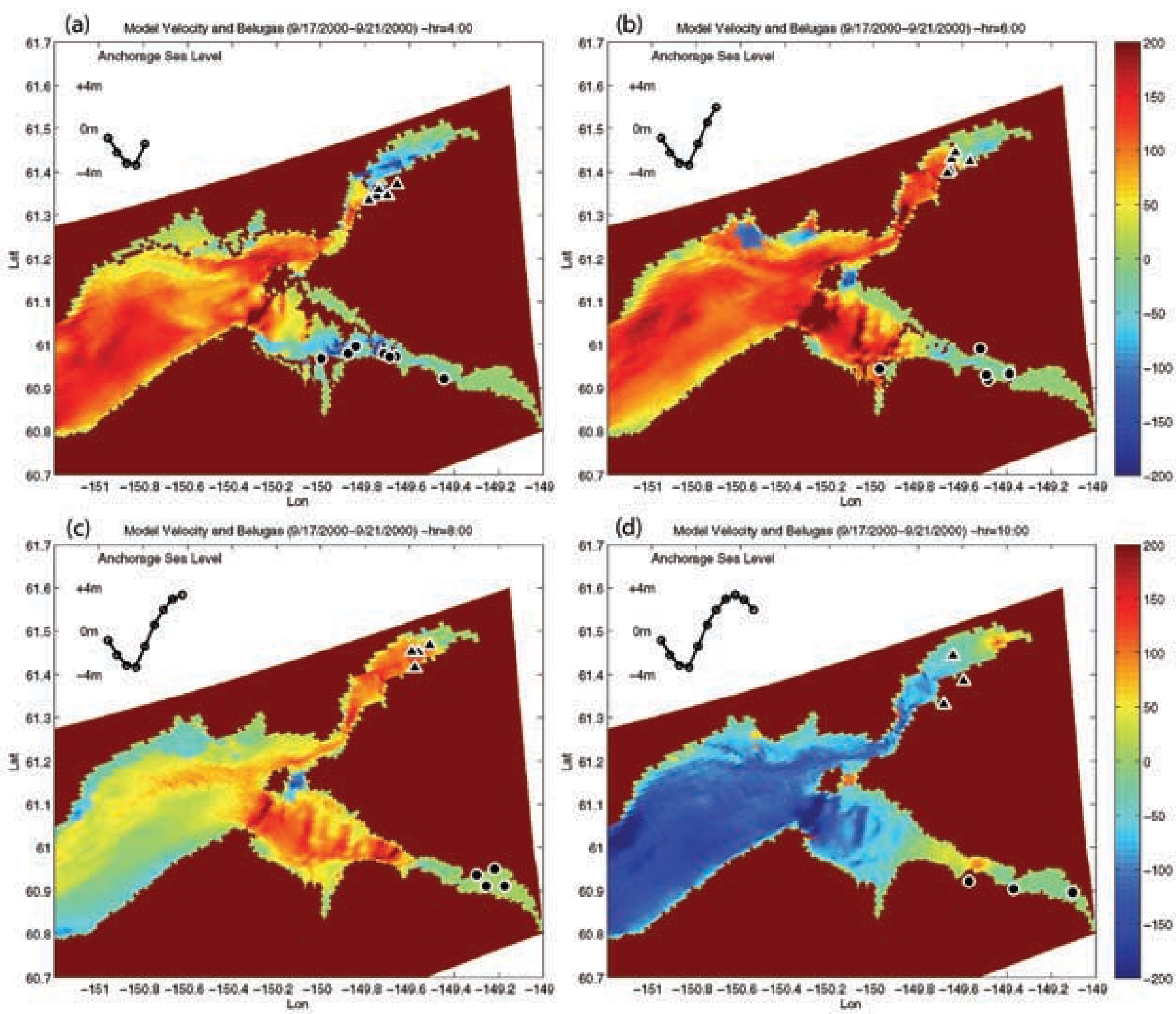


Figure 7. Same as Figure 5, but with color representing water speed in cm s^{-1} along the inlet. Blue shading represents ebbing (velocity direction toward deeper regions), and yellow and red shading represents flooding (velocity direction toward shallow regions, in the east ends of the arms). The tidal front is the area with sharp change from red/yellow to green/blue.

during low tide; during high tide they seem to return to the same river mouth every tidal cycle (at least in this short period) to feed on anadromous fish that may be more abundant there than in the deep part of the inlet.

The results presented here represent a preliminary study to test the usefulness of the model in helping to monitor the belugas' movements. Future extension of this study will include analyses of much longer simulations (a few years) that will shed more light on environmental impacts as well as on seasonal and interannual variations in the belugas' movements. These studies will increase our understanding of the belugas' behavior on longer time scales and the potential impact of climatic changes, as well as the impact of future shoreline developments in the region.

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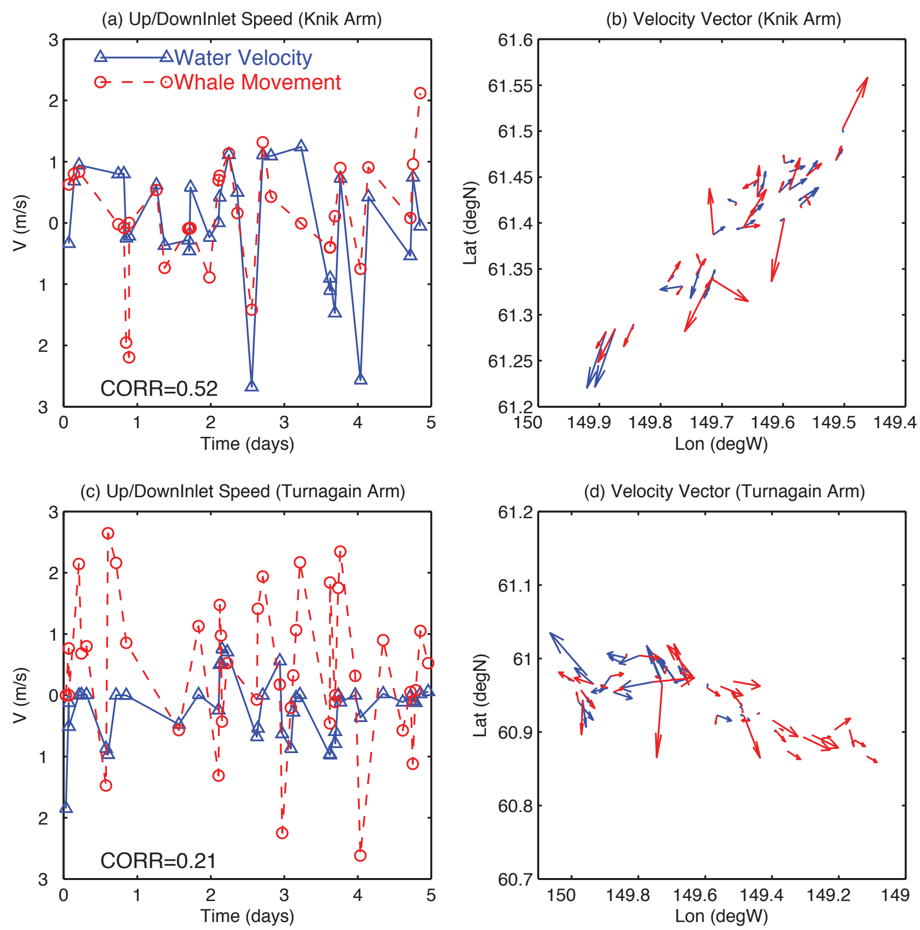

Figure 8. Comparison of simulated water velocity (blue solid lines and blue arrows) and estimated whale movement speed (red dashed lines and red arrows) for Knik Arm (upper panels) and Turnagain Arm (lower panel). Time series of the along-arm velocity component are shown in (a) and (c) (positive/negative values for flooding/ebbing), and vectors are shown in (b) and (d) (maximum vector length is ~ 3 m s^{-1}).

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