STRUCTURE AND EVOLUTION OF DREDGED RIP CHANNELS

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Abstract

Currents observed for several days in and near a channel dredged across the surf zone initially were alongshore to the north, then changed to alongshore feeders converging at an offshore-directed rip current, followed by near zero flows. The strongest flows in the rip current migrated alongshore to the north before the rip weakened. A new method is developed to obtain temporally dense maps of the channel bathymetry by updating a spatially dense initial survey with the bathymetric change (e.g., erosion and accretion) estimated from a spatially sparse array of continuously measuring altimeters. Maps produced by this update method are more accurate than maps obtained by spatially interpolating the sparse altimeter measurements at any given time. The resulting high temporal resolution bathymetric estimates suggest the alongshore migration of the rip current may have been caused by migration of the channel.

Key words: rip channel, rip current, bathymetric surveys, altimeters, surfzone

1. Introduction

Strong, narrow offshore-directed surfzone flows (rip currents) often are associated with bathymetric depressions in alongshore-parallel sandbars (Haller et al., 1997; Chen et al., 1999; MacMahan et al., 2006; Austin et al., 2010; Dalrymple et al., 2011). Despite the importance of bathymetry in controlling rip currents, the evolution of rip channels has not been investigated in detail in the field, partially owing to the difficulty of performing surveys in the surf zone, especially during periods with large waves and strong currents. Nearshore hydrodynamic model results are sensitive to bathymetry (Plant et al., 2002; Plant et al., 2009), which controls wave shoaling, refraction, and breaking, and consequently controls wave-driven setup and flows. In particular, large model errors are associated with poor temporal resolution of bathymetric changes, especially during storms (Wilson et al., 2010). Although video can be used to monitor the evolution of nearshore sand bars (Lippmann and Holman, 1989), most techniques to survey vertical changes in sand levels are restricted to calm conditions preceding and following large wave events, and thus often the largest bed-evolution events are left unresolved in time. For example, the generation of a sandbar may be inferred from a pair of surveys before and after a large wave event (Thornton et al., 1996), but the missing details about the temporal changes in the bathymetry may be essential to understanding both the hydrodynamics and the morphological response.

Fixed altimeters able to record the distance between the sensor and the seafloor during stormy conditions can be used to add temporal bed-level information at a set of spatial locations (Gallagher et al., 1996; Gallagher et al., 1998a; Gallagher et al., 1998b). However, observational programs usually deploy altimeters at relatively few locations, with spacing often determined by initial bathymetry, and thus may not resolve the spatial structure of the bathymetry sufficiently. Here, a method for updating an initial, spatially dense watercraft survey (perhaps performed in calm conditions on the day altimeters are deployed) with temporally continuous, spatially sparse altimeter estimates of the seafloor elevation is presented. The update method has smaller errors reproducing a subsequent spatially dense watercraft survey (perhaps performed after a storm) than simply interpolating between altimeter estimates of the seafloor location at any particular time.

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2. Field Observations

The propellers from a Vietnam-era landing craft ("MIKE" boat) were used to dredge large shore-perpendicular channels in 1- to 3-m water depth on a long straight Atlantic Ocean beach at the US Army Corps of Engineers Field Research Facility near Duck, NC, USA. Five channels were dredged in July and August 2012. The channel sizes varied, and were on average 2-m deep, 30-m wide in the alongshore, and 50-m long in the cross-shore. The ambient bathymetry was either a low-tide terrace (e.g., Figure 1) or a small sandbar and nearshore trough. Pressure sensors colocated with current meters and current profilers were deployed in and outside of the channels (Figure 1), and altimeters and a watercraft survey system recorded bathymetric evolution (see section 3 for more information on survey techniques). Significant wave heights (4 times the standard deviation of sea-surface-elevation fluctuations) just offshore of the channels ranged from 0.5 to 1.5 m, centroidal frequencies ranged from 0.09 to 0.20 Hz, wave directions ranged from approximately -35 to +35 degrees relative to shore normal, and directional spreads (Kuik et al., 1988) ranged from about 10 to 30 degrees.

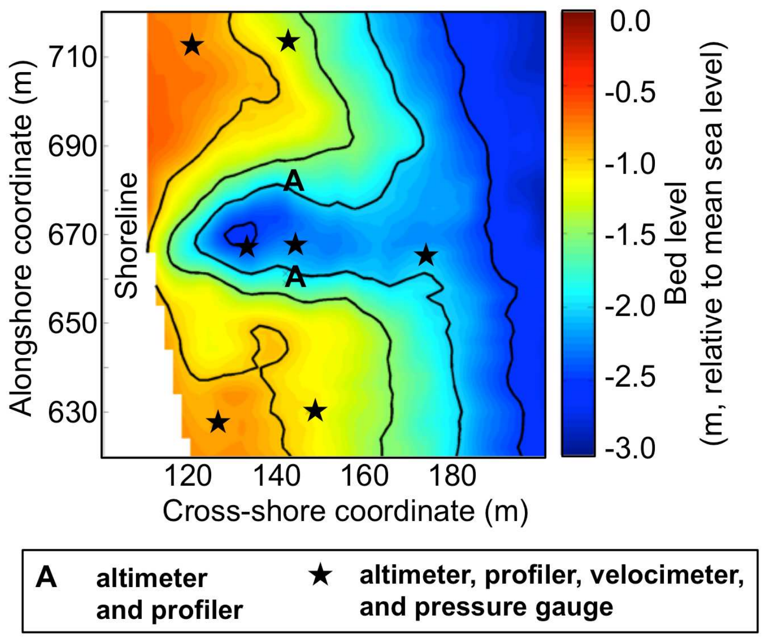

Figure 1. Contours of water depth (relative to mean sea level, black curves and color bar on right, where red is shallow, blue is deep) as a function of cross- and alongshore coordinate. The shoreline is on the left, and the dredged channel is centered near cross-shore coordinate 140 m and alongshore coordinate 670 m. Symbols (given in the legend) show positions of different combinations of altimeters, profilers, velocimeters, and pressure gauges for a typical deployment (sometimes there were more or fewer sensors).

As waves propagated toward the shoreline across the dredged bathymetry, they broke in the shallow water on the sides of the channel, but not over the deep water in the channel (Figure 2). Thus, there is more set up (Longuet-Higgins and Stewart, 1964) of the mean water level on the sides of the channel than in the center, sometimes driving a circulation pattern consisting of a rip current flowing offshore through the channel fed by alongshore currents flowing toward the channel. When waves approached the shoreline from approximately 35 degrees relative to shore normal, strong alongshore currents were generated (Longuet-Higgins, 1970; Thornton and Guza, 1986) that crossed the channel (Figure 3A). Mean alongshore flows over the channel were weaker than those on the sides of the channel, perhaps owing to divergence of the flow over the deeper water in the channel. When waves were more normally incident (a few degrees from shore normal, e.g., Figure 2), the alongshore flows converged on the channel, driving a rip current (Figure 3B&C). Alongshore current speeds were 0.1 to 1.0 m/s, and the rip currents ranged from 0.1 to 1.0 m/s (depending on wave height and tidal elevation), and lasted from 1 to 36 hours.

For some cases, the alongshore location of the maximum offshore-directed flow migrated in time (compare Figure 3B with Figure 3C, separated by 3 hours), possibly owing to evolving bathymetry in and near the channel. During the strongest rip currents, waves were too big to operate the watercraft safely, and thus there are no spatially dense bathymetric surveys during the time when the rip current appeared to migrate (Figure 3). However, the altimeters operated continuously, and thus may provide sufficient information to estimate bathymetry between watercraft surveys.

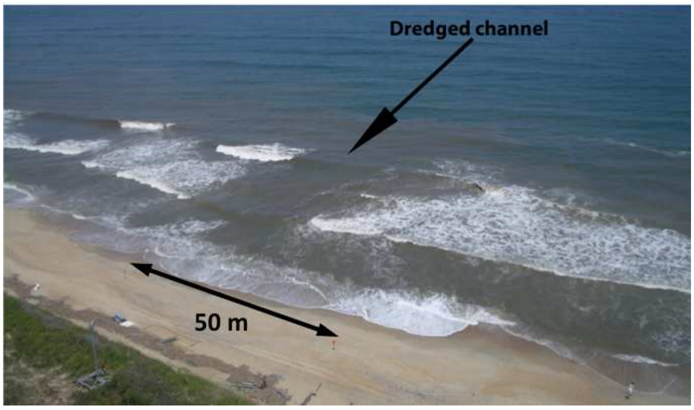

Figure 2. Normally incident waves breaking (white foam) on the shallow sides of the deeper dredged channel (arrow).

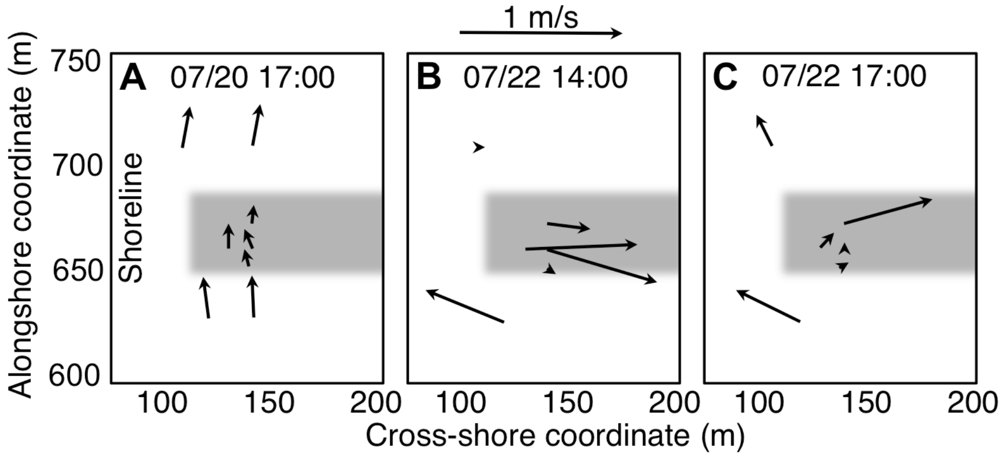

Figure 3. Velocity (arrows showing 1-hr mean flows, scale above center panel) as a function of alongshore and cross-shore coordinate. The grey shaded regions show the approximate location of the channel. The circulation patterns are (A) strong alongshore flows crossing the channel, (B) a strong rip current flowing offshore in the channel, and (C) the maximum of the rip current appears to have moved northward (toward the top of the figure).

3. Survey Techniques

For each experiment, the bathymetry was surveyed with a watercraft before sensors were deployed, and daily afterwards except when wave heights were too large for safe operations. The watercraft surveys were performed along cross- and alongshore tracks, and the resulting bathymetric maps have 5 m horizontal resolution and 0.05 to 0.10 m vertical accuracy. To map the shoreline, surveys were performed during high tide when possible. The 24 personal watercraft survey maps (Table 1) spanned roughly 200 m in the alongshore, centered at the channels, and extended from near the high-tide line to about 100 to 200 m offshore. In addition, estimates of the seafloor location were obtained every minute from an array of up to 14 altimeters deployed in a grid with roughly 10 to 30 m spacing centered at the channel (e.g., Figure 1). When possible, altimeters were spaced more densely across the channel to resolve the channel cross section.

Table 1. Summary of bed-level observations from channel dredging experiments, including the date and time of the dredging, date and time of altimeter deployments and recovery, the number of altimeters ("count") deployed and their average horizontal spacing, date and time of spatially dense watercraft surveys, and comments about the infill of the dredged channels. Format for date and time is month/day-of-month hour:minute.

Channel dredging Date and Time	Altimeter Deployment Deployed; Recovered	Altimeters Count; Spacing	Surveys Date and Time	Bathymetry Comments
06/28 13:00	06/29 11:00; 07/05 09:00	9; 20 m	06/28 13:00; 06/29 15:00; 06/30 07:00; 07/02 08:00; 07/03 09:00; 07/05 12:00	Channel filled steadily and slowly
07/07 11:00	07/08 09:30; 07/17 09:00	14; 20 m	07/07 12:00; 07/08 12:00; 07/09 12:00; 07/10 15:00; 07/13 16:00; 07/17 16:00	Channel filled rapidly on 07/12
07/18 18:00	07/19 18:00; 07/23 10:00	6; 10 m	07/18 18:00; 07/20 10:00; 07/23 12:00	Channel filled rapidly on 07/21
07/24 11:00	07/24 17:40; 07/30 09:00	11; 20 m	07/24 12:00; 07/26 14:00; 07/27 15:00	Channel filled rapidly on 07/25
07/30 12:30	07/31 11:00; 08/06 05:45	11; 20 m	07/30 13:00; 07/31 08:00; 08/02 09:00; 08/03 09:00; 08/04 10:00; 08/06 12:00	Channel filled steadily and slowly

3.1 Personal watercraft

Personal watercraft equipped with sonar and GPS (MacMahan, 2001; Dugan et al., 2001; Lippmann and Smith, 2008) were used to obtain spatially dense surveys of the nearshore and surfzone bathymetry. Errors are approximately 0.05 m in both the horizontal and the vertical. Although watercraft surveys are accurate and spatially dense, they can be performed only during relatively calm conditions and in the absence of bubbles that interfere with sonar returns from the seafloor. The watercraft move at several meters per second, and must estimate the distance to the seafloor based on only one or a few sonar returns at each horizontal location. Thus, the surveys are not accurate in depths for which waves are breaking, including across a wide surf zone during storms, and near the shoreline during calm conditions.

3.2 Fixed-in-space altimeters

Here, two types of acoustic altimeters were deployed at fixed locations in the surf zone. At some locations, the backscattered signal strength from a downward looking acoustic Doppler current profiler (Nortek Aquadopp, deployed on a cantilever on a pipe, Figure 4A) was used to estimate the distance between the acoustic transducer and the seafloor, a source of a strong echo (Figure 4B). The profilers recorded one-minute-averaged echo amplitude in 0.10 m vertical bins for each of three 2 MHz beams separated by 22° (Figure 4A). The seafloor location was estimated as the three-hour running mean of the average of the one-minute bottom estimates from each beam. The one-minute bottom estimates were made with a peak-finding algorithm that selects the strong return from the seafloor. Linear interpolation was used to fill gaps (less than 1% of samples) when the bottom signal was obscured (e.g., by bubbles, temporary burial, or if the transducer came out of the water in wave troughs at low tide). The vertical resolution is on the order of the profiler bin size, 0.10 m, and the estimates of the distance to the bottom are fairly robust in the presence of high concentrations of wave-generated bubbles (Figure 4B).

At other locations, single-beam acoustic altimeters recently developed at the Woods Hole Oceanographic Institution (WHOI) were deployed. The WHOI altimeters record echo amplitude from a 1 MHz beam in 0.01 m bins at 2 Hz. The instruments were deployed on a cantilever on a pipe (Figure 4C). The 2 Hz amplitude records were averaged every minute in post processing, and the bottom signal (Figure 4D) was estimated using a peak-finding algorithm followed by a three-hour running mean, resulting in approximately 0.05 m resolution.

The WHOI altimeter bottom echo signal is fairly robust even in the presence of significant amounts of breaking-wave-induced bubbles and suspended sediments. Sometimes the bottom return is obscured by the presence of bubbles during large wave events (Figure 4E), but the loss of the signal is intermittent and, partly owing to the rapid (2 Hz) sampling, the bottom can be found within almost every one-minute interval. Sometimes, the altimeter was deployed such that the transducer came out of the water at low tide or during the passage of a wave trough. There is no signal when the altimeter is out of the water, but as long as the altimeter occasionally is submerged in wave crests, there are sufficient bottom returns to estimate the bed elevation (Figure 4E). In addition to detecting the seafloor, the WHOI altimeters may provide a qualitative measurement of bubbles and suspended sediment (Figures 4D&E) (Ha et al., 2011).

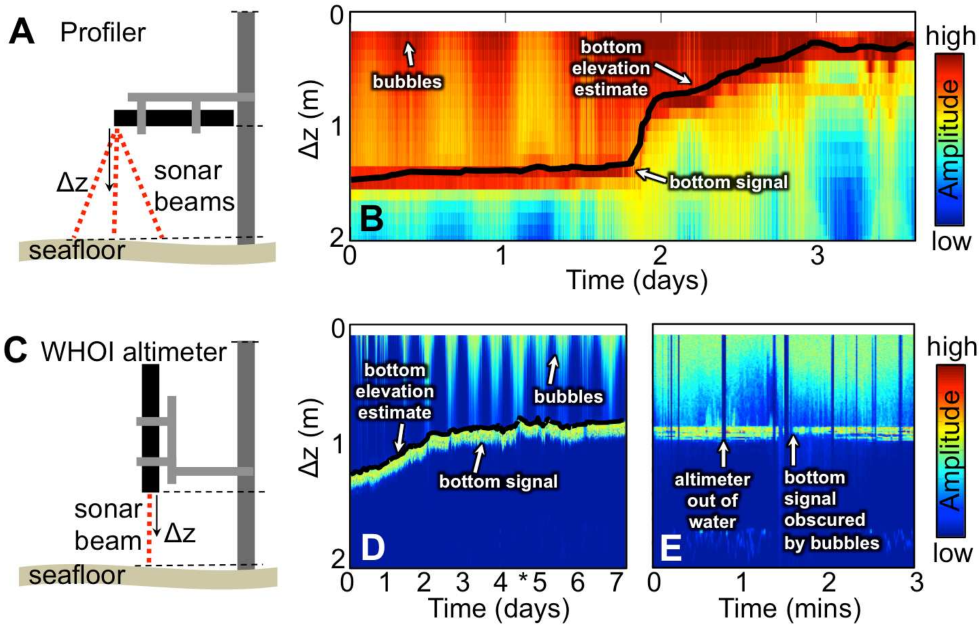

Figure 4. (A) Sketch of acoustic Doppler current profiler (ADCP) used as an altimeter, (B) amplitude of echo returns from one of three beams of the ADCP (color scale on the right, red is strong returns, blue is weak) as a function of depth below the altimeter and time showing the estimated location of the seafloor (black curve), (C) sketch of the WHOI altimeter, and (D and E) amplitude of echo returns from the WHOI altimeter (color scale on right) as a function of depth below the altimeter and time for (D) 7 days of data (black curve is seafloor location) and (E) 3 minutes of data. The * on the time axis of D (between time = 4 and time = 5 days) corresponds to the time of the time series in E.

4. Altimeter updates to survey data

Bed-level estimates at a few spatial locations can represent nearly planar bathymetry with reasonable accuracy. However, bed-level estimates at just a few spatial locations may not be sufficient to resolve features in bathymetry with substantial structure, such as a bar and trough, or a trench or depression. Spatially dense information about the structure of the bathymetry at one time (e.g., from a watercraft survey) may be used in combination with spatially sparse, but temporally dense accretion and erosion measurements to produce two-dimensional bathymetric maps (Section 4.1) or cross sections of bed levels along one dimension (Section 4.2) at arbitrary times since the dense survey.

To produce estimates of the bathymetry every hour, the changes in bed level estimated from the differences between hourly seafloor locations from fixed altimeters are interpolated onto a horizontal grid with 2 m resolution. The map of bathymetric change is then added to the previous updated map (or for the first hour, to the initial spatially dense survey) to provide an updated estimate of the bathymetry every hour. This approach is called the “update” method. Alternatively, estimates of the bathymetry at any time can be obtained by linearly interpolating in space between altimeter estimates of the bed level (“interpolation” method).

4.1 Channel maps

To assess the accuracy of two-dimensional maps made with the two methods that use the fixed altimeters, maps made using the interpolation method and maps made with the update method were compared with surveys for the 51 possible pairs of temporally separated spatially dense surveys. The update method has smaller errors [the average root-mean-square (rms) error with spatially dense surveys is 0.15 m] and usually (35 out of 51 comparisons) performs better than interpolation (average rms error with spatially dense surveys is 0.20 m). The average rms difference between final and initial spatially dense surveys is 0.24 m. In addition, the rms error between an updated map and a final survey is smaller than the rms change between the initial and final dense survey for 47 of 51 comparisons, whereas the rms error between an interpolated map and a final dense survey is larger than the rms change between the initial and final survey for 28 of 51 comparisons. Thus, for more than half the cases studied here, the interpolated map is not better than assuming no bathymetric change between the dense surveys.

Sometimes the altimeter interpolation maps do not resolve the channel seen in the dense surveys (compare Figure 5B with 5A, and Figure 5D with 5C), whereas maps made using the update method resolve the channel (compare Figure 5E with 5C). At other times, both the interpolated and the updated maps resolve the basic features of the channel, but the updated maps resolve more of the details of the channel shape and maximum depth, and are in better agreement with the survey (Figure 6).

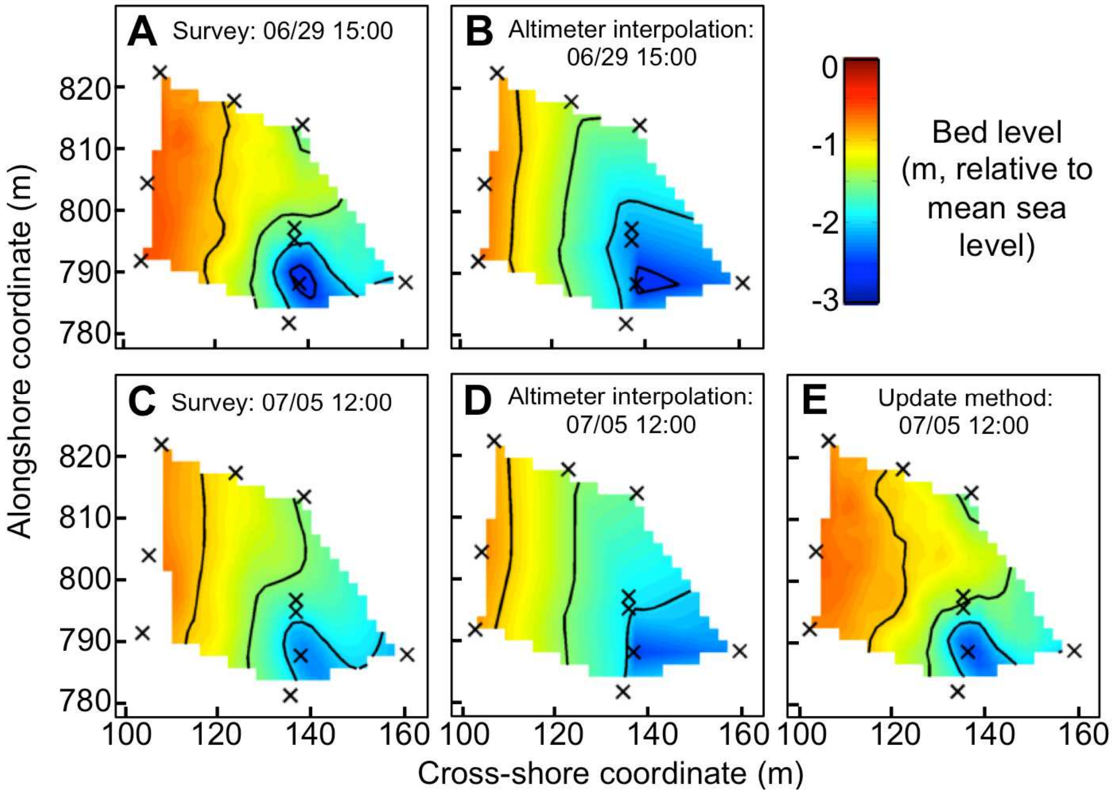

Figure 5. Contours of bed level (relative to mean sea level) as a function of alongshore and cross-shore coordinate. A color scale is shown in the upper right corner, and black curves are drawn every 0.5 m. Bed-level data are shown only in the region bounded by altimeters, where interpolation is possible. A) Initial map from a spatially dense survey on 06/29 15:00, B) map based on interpolation of altimeter bed levels observed 06/29 15:00, C) final map from a spatially dense survey on 07/05 12:00, D) map based on interpolation of altimeter bed levels observed on 07/05 12:00, and E) map based on the update method between initial and final dense surveys. Crosses are positions of altimeters. The rms change between initial and final spatially dense surveys (A, C) is 0.14 m. The rms error between the altimeter interpolation map (D) and the final survey (C) is 0.21 m. The rms error between the update method map (E) and the final survey (C) is 0.11 m.

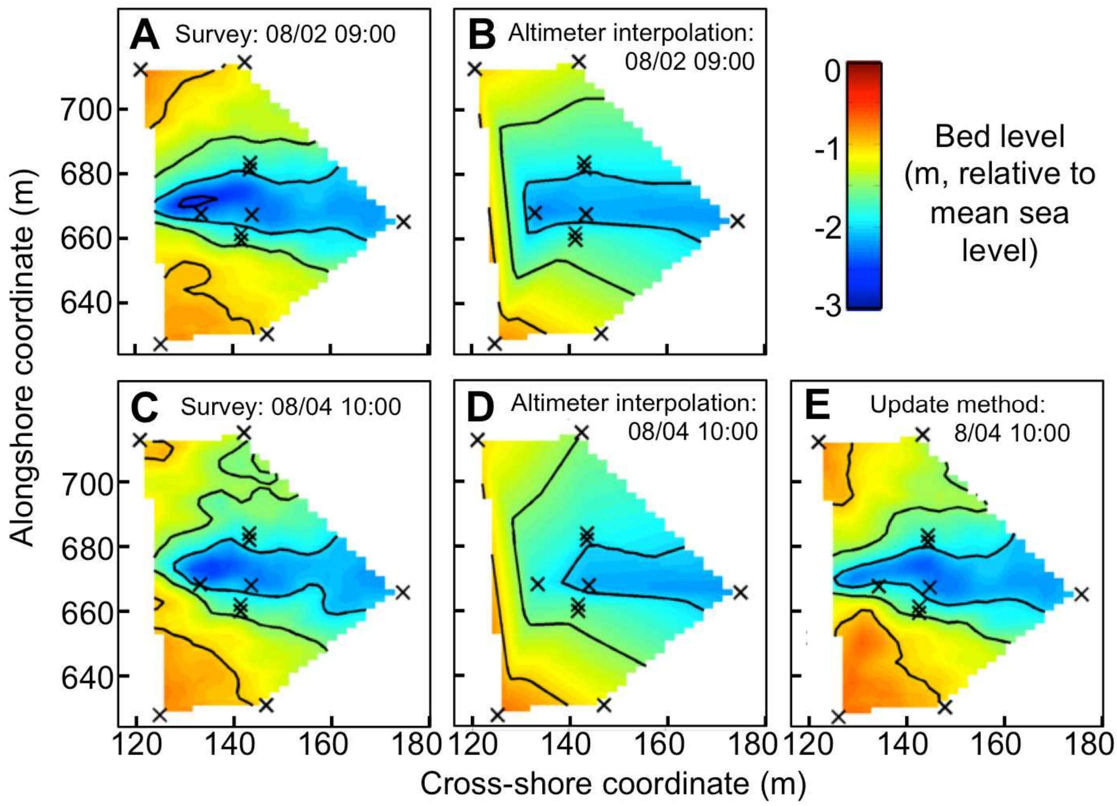

Figure 6. Contours of bed level (relative to mean sea level) as a function of alongshore and cross-shore coordinate. A color scale is shown in the upper right corner, and black curves are drawn every 0.5 m. Bed-level data are shown only in the region bounded by altimeters, where interpolation is possible. A) Initial map from a spatially dense survey on 08/02 09:00, B) map based on interpolation of altimeter bed levels observed 08/02 09:00, C) final map from a spatially dense survey on 08/04 10:00, D) map based on interpolation of altimeter bed levels observed 08/04 10:00, and E) map based on the update method between initial and final dense surveys. Crosses are positions of altimeters. The rms change between initial and final spatially dense surveys (A, C) is 0.16 m. The rms error between the altimeter interpolation map (D) and the final survey (C) is 0.18 m. The rms error between the update method map (E) and the final survey (C) is 0.13 m.

4.2 Channel cross sections and channel evolution

The evolution of the channel cross section is investigated by generating hourly one-dimensional sections across the channel (results are similar to taking cross sections from the two-dimensional maps). Similar to the two-dimensional maps, the updated cross sections have smaller average rms errors than interpolated cross sections (interpolation error: 0.19 m, update error: 0.14 m, survey change: 0.23 m), and usually are better than interpolation (36 out of 51 comparisons). Rms errors in updated maps are smaller than rms survey changes in 37 of 51 cases, whereas rms errors in interpolated maps are larger than rms survey changes in 29 of 51 cases.

The hourly update maps provide information about the temporal evolution of the channels between the spatially dense surveys (separated by 24 hours or more). For example, for the channel dredged on 07/18, dense surveys show that the channel filled and moved northward between 07/18 and 07/23 (Figure 7). However, these surveys do not resolve the temporal changes caused by the relatively large waves and rip current (Figure 3) that were observed during the 5 days between dense surveys. In contrast, the hourly updated maps (Figure 8) show the bathymetric change in higher temporal resolution over the 5-day period between dense surveys.

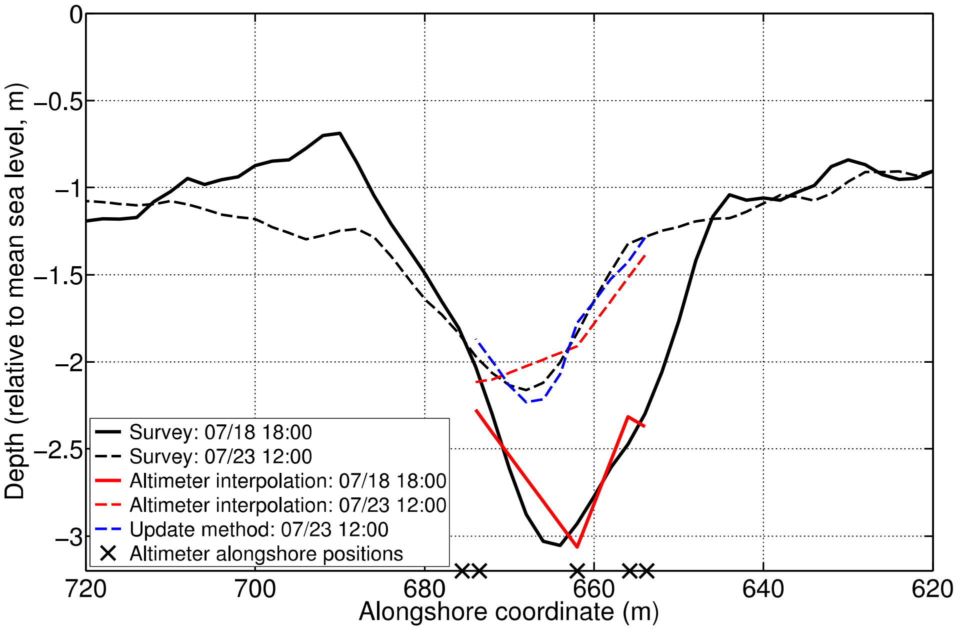

Figure 7: Depth of seafloor across the channel *versus* alongshore coordinate. Solid black curve is the initial spatially dense survey, red curve is an estimate of the bathymetry from linear interpolation of altimeters (positions given by the crosses on the x-axis) at the time of the initial dense survey, dashed black curve is a spatially dense "final" survey (5 days after the initial survey), dashed red curve is the estimate of the final survey from interpolating between fixed altimeter estimates at the time of the final survey (rms difference = 0.12 m), and blue dashed curve is the estimate of the final survey using the altimeters and the update method (rms difference = 0.07 m). The rms difference between initial and final dense surveys is 0.90 m.

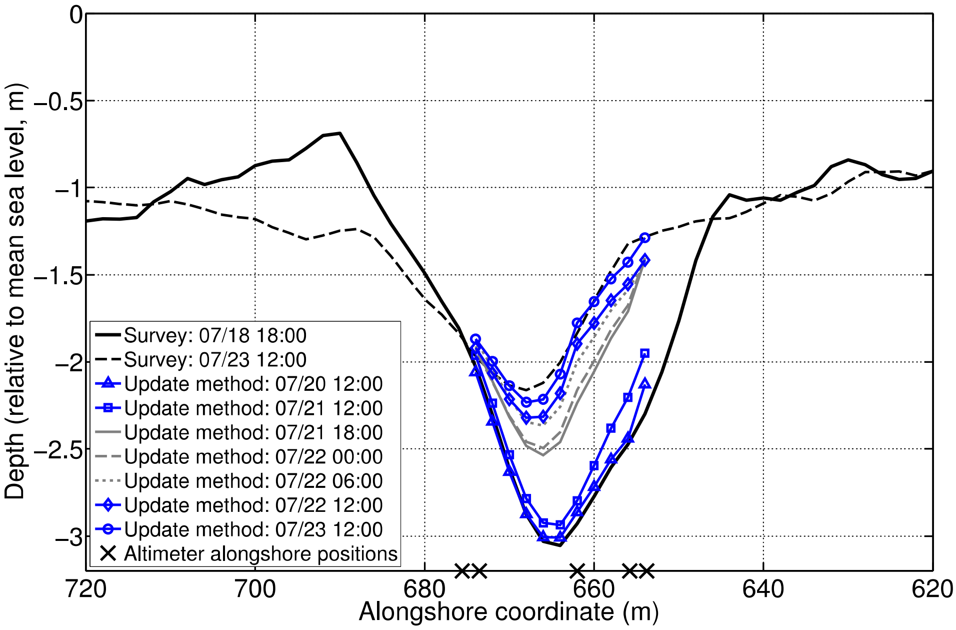

Figure 8. Depth of seafloor across the channel *versus* alongshore coordinate. Solid black curve is the initial spatially dense survey on 07/18 18:00, dashed black curve is the final spatially dense survey on 07/23 12:00. Blue curves are cross sections using the update method every 24 hours from 07/20 12:00 to 07/23 12:00. Grey curves are cross sections using the update method every 6 hours between 07/21 12:00 and 07/22 12:00. The channel fills and migrates northward (north is to the left on the x axis) most rapidly between 07/21 12:00 and 07/21 18:00.

The updated cross sections indicate that the rates of channel infill (not shown) and migration (Figure 9A) varied in time. Gaussian fits to hourly updated cross sections are used as a proxy to determine the channel position (Figure 9A) and (not shown) channel depth, channel width, and ambient bed elevation. For the fits, the unknown bed elevations at grid points north and south of the region spanned by the altimeters are set to the average dense survey bed elevation at each grid point. Changes in this choice (including fitting only in the region spanned by altimeters) do not change the results qualitatively.

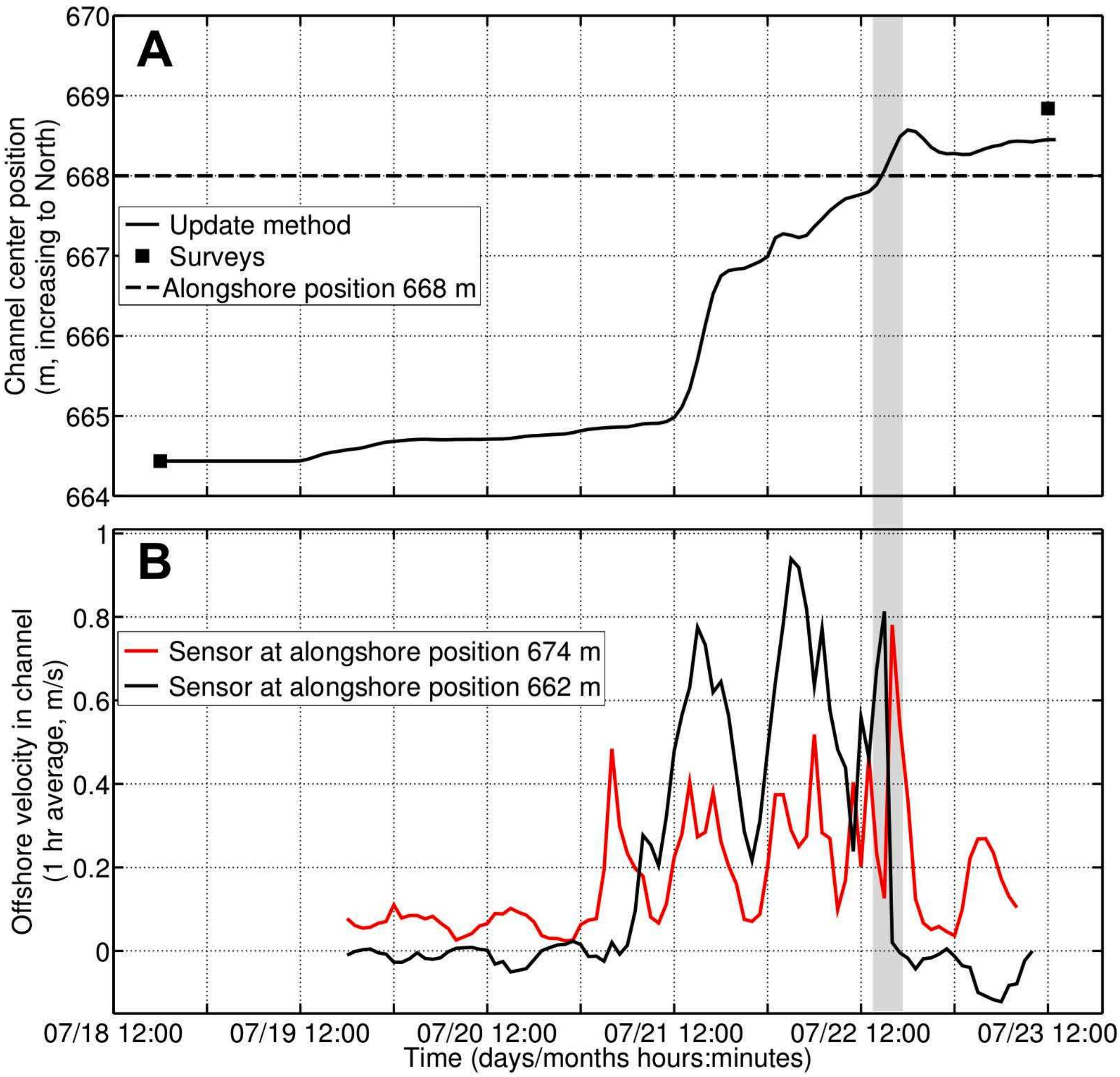

Figure 9: (A) Channel center position based on altimeter updated cross sections (curve) and based on spatially dense surveys (symbols), and (B) offshore-directed velocity [red curve (alongshore coordinate y = 674 m) is northern sensor and black curve (y = 662 m) is the sensor at the initial center of the channel (y = 664 m)] *versus* time. The horizontal dash line in (A) is the mid-way point between the northern and center sensors. The channel center position and flows are shaded gray when the channel center reaches the mid-way point at about 07/22 13:00.

Flows in the rip channel fluctuated with the tidal elevation, with the strongest flows occurring near low tide (Figure 9B, low tides with a strong offshore-directed rip occurred at about 07/21 03:00, 07/21 14:00, 07/22 03:30) when wave breaking was strongest on the shallow sides (e.g., Figure 3). When the channel center moved north of the mid-way point between the center and the northern sensor, the maximum measured flow shifted from the center to the northern sensor (shaded area), suggesting that the rip current jet also shifted northward (Figure 9B). In particular, the current magnitude decreased rapidly at the central sensor (Figure 9B, black curve) and increased at the northernmost sensor (Figure 9B, red curve), suggesting a northward shift in the position of the rip jet. The channel filled (Figure 8) by almost 1.0 m during the 27 hours that the channel center rapidly migrated north (e.g., from 07/21 12:00 until about 07/22 15:00). Significant wave heights just offshore of the channel were between 0.5 and 1.0 m and ranged from within 15° of shore normal between 07/21 06:00 and 07/22 06:00 to 35° from the south during the previous and following 24 hours. The channel may have migrated owing to divergences in sediment transport caused by divergences in alongshore flows or by divergences in sediment transported in the cross shore by the rip current.

6. Summary

Significant changes in surfzone bathymetry often occur when waves and currents are too large to obtain spatially dense bathymetric surveys (e.g., with watercraft). Spatially sparse, continuously sampling, fixed-in-space altimeters can be used to make linearly interpolated bed-level maps at any given time. Alternatively, initial (pre-storm) spatially dense bathymetric maps can be updated by adding a map of the bathymetric change since the initial survey. The change map is estimated by spatially interpolating the change (from the previous map) observed at each altimeter. By adding a change map to the initial survey, an estimate of the bathymetry can be made at any given time. For evolving dredged channels in the surf zone, these updated maps are closer to dense spatial surveys made after the initial survey than are maps made by interpolating altimeter estimates of the bed level at the time of the final dense surveys. Bathymetry estimated using the update method to span a several day gap for which waves were too large to perform dense surveys suggests that the observed migration of the maximum of a rip current jet in a channel excavated across the surfzone seafloor may be associated with the migration of the channel.

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