Currents in a small tidal-flat channel

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ABSTRACT:

Near-bottom currents observed on a tidal flat are compared with those observed 50 m away inside a shallow (0.25 to 0.40 m deep) channel. For water depths between 0.5 and 2.5 m (when both current meters are submerged), current speeds 0.13 m above the bed on the flat are about 30% greater than those observed 0.13 m above the bed in the channel, and are approximately equal to those observed 0.58 m above the channel bed (0.26 m above the flat elevation). Flow directions on the flat are similar to those in the channel. For flows parallel to the channel axis, the ratio of speeds 0.13 m above the bed on the flat to those 0.13 m above the bed in the channel decreases from about 1.4 to about 1.1 with increasing water depth, consistent with conservation of mass. For flows directed across the channel axis, the ratio of speeds increases from about 1.3 to about 2.2 with increasing water depth. The corresponding ratio of the vertical velocity variances (a proxy for turbulence) decreases from about 1.5 to about 0.2, suggesting that the turbulence near the bed of the channel is greater than that near the bed of the flat for water depths greater than about 1.0 m. In contrast, for along-channel flows, the channel and flat turbulence levels are similar. Drag coefficients estimated with the vertical velocity variance or with a cross-shore momentum balance are approximately 70% larger in the channel than over the visually smoother flat.

KEYWORDS: tidal flat, flow in channels, drag coefficient
1. Introduction

Tidal flats (Figure 1) are found on coasts where there is a large supply of fine sediment, a large tidal range in water elevation, and low-to-moderate wave energy. Healthy tidal flats are critical for many species of wading birds and coastal fish. Furthermore, tidal flats help protect coastal areas, both by providing a buffer at the shoreline and by influencing the coastal sediment budget. Tidal flats often are covered with dendritic branching channels (complex braids in Figure 1) that direct both river water and ebbing tidal flows offshore. Observations have suggested that channel spacing is related to channel width, cross-sectional area, discharge, and watershed area (Fagherazzi et al. 1999, Rinaldo et al. 1999). Numerical model simulations and a linear stability analysis of channels on short, wide mesotidal flats, such as those along the Dutch coast, suggest that the width and spacing of branching channels increases with increasing bottom slope, increasing Shield’s number, and decreasing depth (Marciano et al. 2005).

Previous observations of tidal channels have focused on flows in marshes (Bayliss-Smith et al., 1979, Healey et al. 1981, Leopold et al. 1993; Fagherazzi et al., 2008), geomorphology (Bridges and Leeder 1976, Fagherazzi and Furbis 2001, Fagherazzi and Sun 2004, and many others), internal waves (Adams et al. 1990), tidal constituents (Blanton et al. 2002), stratification (Ralston and Stacey 2005a,b, 2006), and turbulence (Ralston and Stacey 2005a,b, 2006). Numerical models suggest that flows in larger channels are stronger than the flows across the flats (Fagherazzi et al. 2003, D’Alpaos et al. 2006), resulting in complicated
patterns of circulation and channel-flat exchanges. Observations in a 0.5- to 1.2-m deep, 10-m wide channel and on the adjacent muddy tidal flat (Mariotti and Fagherazzi, 2010) suggest lateral flow toward the channel increases channel discharge as the flat drains during ebb tide. Although flows in the channel usually were low, pulses of strong along-channel flow were observed as the water level approached the elevation of the flat. Pulses during ebb tides were stronger than those during flood tides.

Despite their potential importance as pathways for sediment transport (Wells et al. 1990, Christiansen et al. 2000, Hood 2006, Green and Coco 2007, Ralston and Stacey 2007, and many others) and as roughness elements affecting the large-scale flow (Whitehouse et al. 2000), there are few observations of currents in small dendritic channels. In a small channel in the salt marshes and mudflats of San Francisco Bay, observations of currents were made along 3 cross-channel transects for two few-day (Ralston and Stacey 2005b) and two 2-week periods (Ralston and Stacey, 2006). Owing to the curvature of the channel, the larger-scale flow changed from mostly along-channel to across-channel between the 3 transects, allowing investigation of flows with different orientations to the channel axis. Turbulence increased for across-channel flows, and for some conditions flows in the channel were smaller than those on the neighboring flat (Ralston and Stacey, 2005b, 2006). Here, near-bed velocity observations obtained over a 6-week period on the sandy Skagit Bay tidal flat (Figure 1) are compared with flows observed in a nearby small channel. Tidal flow directions rotated 360° counterclockwise during each tidal cycle, enabling the effect of flow direction on current speed and turbulence to be examined at a single location.
2. Field Observations

Observations of near-bottom velocity and pressure were obtained in a small channel and on the neighboring tidal flat (Figures 2 and 3) in Skagit Bay, Puget Sound, WA (Figure 1) between July 20 and Aug 28, 2009. The instruments were sampled at 2 Hz, and the data were subdivided into 512-s (8.5 min) subsections. The tidal range in Skagit Bay is approximately 4 m, and at the mid-flat location of the instruments the range is about 2.5 m. The current meters required approximately 0.25 m water depth to operate. After discarding data when the current meter on the flats was not submerged owing to low tides, and when sensors were fouled by algal mats (despite daily cleaning) or were being maintained, approximately 1800 subsections of data were available for analysis.

Hourly boundary finding by the downward-looking acoustic current meters, CTD casts, and large-scale bathymetric surveys indicate the channel bed ranged from approximately 0.25 to 0.40 m below the surface of the tidal flat. Almost-daily low-tide visual observations also indicate that the channel evolved slowly, deepening about 0.15 m and migrating toward the east.

Flow directions observed on the flat were similar to those observed in the channel (Figure 4a). However, across-channel flows observed on the flat were about 40% greater than those observed in the channel (Figure 4b), and along-channel flows on the flat were about 20% greater than those observed in the channel (Figure 4c). Unlike observations in a small (1 – 1.5 m deep, 10 m wide) channel on a muddy tidal flat (Mariotti and Fargherazzi, 2010) and in much larger (> 1 m deep, 100 m wide) channels on both muddy and sandy tidal flats (Ogston
et al., 2010; Geyer et al., 2010), strong pulses of flow in the channel during ebb tide were not observed, neither when both sensors were submerged (Figure 4) nor when water levels dropped below the elevation of the flat (not shown).

The ratio of current speed (defined as the square root of the sum of the squared along- and across-channel flows) observed 0.13 m above the bed on the flat, $U_f$, to that observed 0.13 m above the bed in the channel, $U_c$, increases as the direction of flow rotates from along ($\theta=0^\circ$, where $\theta$ is the angle between flow direction and along-channel orientation) to across ($\theta=90^\circ$) channel (filled circles in Figure 5). However, flows observed about 0.58 m above the channel bed (0.26 m above the flat elevation) (profiler-1 in Figure 3) are approximately the same as those observed 0.13 m above the flat (open squares in Figure 5). Flows 0.83 m above the channel bed (0.51 m above the flat elevation) (profiler-2 in Figure 3) are stronger than those observed 0.13 m above the flat (filled triangles, Figure 5), consistent with increasing flow speeds with increasing distance above the bottom boundary layer. The ratio $U_f/U_c$ is insensitive to the flow direction when $U_c$ is measured 0.58 m or more above the channel bed (Figure 5).

The ratio $U_f/U_c$ depends on the water depth. For currents flowing primarily along the channel axis ($0^\circ < \theta < 40^\circ$), $U_f/U_c$ decreases as the depth increases (Figure 6). Assuming that flows are along-channel and unidirectional without secondary circulation or alongshore (across-channel) gradients, and that near bottom currents are proportional to depth-averaged flows, continuity requires that the flow rate $Q$ over the channel is the same as the rate over the flat:
$Q \propto U_f h_f = U_c (h_f + h_c)$ \hfill (1)

and thus,

$$\frac{U_f}{U_c} = \frac{h_f + h_c}{h_f} = 1 + \frac{h_c}{h_f}$$ \hfill (2)

where $h_f$ and $h_c$ are the depths of the flat and the channel, respectively (Figure 3), and $h_f + h_c$ is the depth of water above the channel bed. The channel depth $h_c$ ranged from about 0.25 to 0.40 m, and the observations are consistent with equation 2 (dashed curves in Figure 6).

In contrast, for currents flowing primarily across the channel ($60^\circ < \theta < 90^\circ$), $U_f/U_c$ increases as the depth increases (Figure 7a). Assuming that the variance of the vertical velocity fluctuations is a proxy for turbulence (see Discussion), the increase of $U_f/U_c$ with depth is accompanied by an increase in the relative amount of turbulence near the channel bed (Figure 7b), consistent with previous observations of flows across a channel (Ralston and Stacey 2005b, 2006). Unlike previous studies (Ralston and Stacey 2005b, 2006), vertical profiles of conductivity and temperature (i.e., the vertical structure of density) measured over the channel were similar to those measured over the neighboring flat. The decreased across-channel flows in the channel relative to those on the neighboring flats may be caused by increased drag over the rougher channel bed, increased generation of turbulence at the edges of the channel (Ralston and Stacey 2005b), or a separation zone near the channel bottom.
3. Discussion

Assuming that vertical velocity fluctuations are a proxy for turbulence, it can be shown that (Nezu and Rodi 1986):

\[
\langle w'w' \rangle = \text{var}(w) \approx C_d U^2
\]  

(3)

where \( w' \) is the fluctuation of the vertical velocity about its mean, angled brackets mean time average, \( \text{var}(w) \) is the variance of vertical velocity, \( C_d \) is the drag coefficient, and \( U \) is the flow speed. Least squares fits to \( \text{var}(w) \) versus \( U^2 \) for all flow directions (not shown, correlation coefficients, \( r^2 \) were between 0.7 and 0.9) result in estimates of the drag coefficient of \( C_d = 0.003 \) on the tidal flat and \( C_d = 0.005 \) in the channel. The high correlation coefficients and the similarity of the estimated drag coefficients to previous results (Collins et al., 1998, Verney et al., 2006, and many others), suggests that \( \text{var}(w) \) can be used as a proxy for turbulence levels for the data discussed here.

An alternative estimate of the drag coefficient can be obtained from the momentum balance. Prior studies [Le Hir et al., 2000; Ertürk et al., 2002] have suggested that the cross-flat momentum balance is dominated by the barotropic pressure gradient and bottom stress such that:

\[
gh \frac{\partial \eta}{\partial x} = C_d U^2
\]  

(4)

where \( g \) is gravitational acceleration, \( h \) is water depth, \( \eta \) is the sea surface elevation relative to the mean sea surface level, \( x \) is cross-flat distance, and \( U \) is the cross-flat flow speed. If flows are across-flat (along-channel) and unidirectional without secondary circulation or along-flat (across-channel) gradients (as assumed above for flows with \( 0^\circ < \theta < 40^\circ \)), it is expected that \( \partial \eta / \partial x \) would be the same over the flat and channel. Thus, the higher flow speeds and smaller...
depth on the flats relative to the channel would need to be balanced by a smaller drag coefficient. For $U/U_c$ about 1.2 (Figure 4C) and average water depths of 1.5 m on the flats (Figure 6) and 1.8 m in the channel, equation (4) suggests that the drag coefficient in the channel should be about 1.7 times that on the flat, roughly consistent with the estimates based on the vertical velocity variance. Visual observations suggest the tidal flat bed was smooth, whereas the channel had numerous bedforms and algal mats with heights of up to about 0.25 m. Thus, the higher turbulence levels and larger drag coefficients in the channel relative to the flats may be related to the channel roughness.

4. Conclusions

Mean currents observed near the bed on a tidal flat were larger than the currents observed near the bed in a nearby small dendritic channel. For flows directed along the channel axis, currents were 20% larger on the flat than in the channel, and the ratio of these flow speeds is consistent with continuity. For flows directed across the channel axis, currents were 40% larger on the flat than in the channel. As the water depth increased, cross-channel flows on the flat increased relative to those in the channel, and vertical velocity fluctuations on the flat decreased relative to those in the channel. Bottom drag coefficients estimated using vertical velocity fluctuations as a proxy for turbulence or using the cross-shore momentum balance are about 70% larger in the channel than on the flat.

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FIGURE CAPTIONS:

Figure 1. Google Earth image of the northwestern half of the Skagit Bay tidal flats, Puget Sound, WA at low tide. The Skagit River discharge and ebbing tidal flows are directed offshore toward the shipping channel by the 1/1000 slope of the tidal flat and by the numerous branching channels. The red arrow points to the location of sensors in a small channel and on the neighboring tidal flat discussed in the text.

Figure 2. (A) A 750-m along-flat by 2000-m cross-flat section of the tidal flat surrounding the small channel (blue curve) discussed in the text. There is approximately 2 m change in elevation across this section of the tidal flat. (B) Elevation versus along-flat distance for the 6 transects indicated by the red curves in A. The symbols are approximate instrument locations. The bathymetric data were obtained with a sonar and GPS mounted on a jet ski.

Figure 3. Instrument locations on the tidal flat and in the channel. Large circles are sample volumes of acoustic Doppler current meters, and small circles are sample volumes in the lowest two bins of an acoustic Doppler current profiler. Pressure gages were colocated with each current meter. The bed of the channel ranged from approximately 0.25 to 0.40 m below the flat surface as the channel eroded and accreted and widened and narrowed. The total water depth in the channel is \( h_f + h_c \), where \( h_f \) is the depth of water above the flat and \( h_c \) is the depth of the channel below the flat.

Figure 4. (A) Direction of flow observed 0.13 m above the tidal flat versus direction of flow observed 0.13 m above the channel bed, and velocity observed on the flat versus velocity
observed in the channel for flows (B) across and (C) along the channel axis. The solid lines are 1-to-1 correspondences, and red dashed lines are least squares fits through the data with slopes of 1.4 (B) and 1.2 (C).

**Figure 5.** Ratio of current speed observed on the tidal flat to that observed in the channel versus flow direction relative to the channel axis. Observations were obtained approximately 0.13 m above the bed of the tidal flat, and 0.13 (filled circles), 0.58 (open squares), and 0.83 m (filled triangles) above the bed of the channel. Bars are 1 standard deviation of the acoustic Doppler velocimeter data. Standard deviations for the acoustic Doppler profilers are similar, but somewhat larger.

**Figure 6.** Ratio of current speed observed on the flat to that observed in the channel versus water depth above the flat for flow directions within 40° of the channel axis. Dashed curves are theoretical speed ratios based on conservation of mass for two values of the depth of the channel $h_c$ below the flat surface. Bars are 1 standard deviation.

**Figure 7.** Ratio of (A) current speed and (B) vertical velocity variance observed on the flat to that observed in the channel versus water depth on the flat for flow directions greater than 60° relative to the channel axis. Bars are 1 standard deviation.
Figure 2
Figure 4

(A) Scatter plot of flat flow direction (deg) vs. channel flow direction (deg).

(B) Cross channel scatter plot of velocity on the flat (m/s) vs. velocity in the channel (m/s).

(C) Along channel scatter plot of velocity on the flat (m/s) vs. velocity in the channel (m/s).