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Nearshore sticky waters

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ABSTRACT

Wind- and current-driven flotsam, oil spills, pollutants, and nutrients, approaching the nearshore will frequently appear to slow down/park just beyond the break zone, where waves break. Moreover, the portion of these tracers that beach will do so only after a long time. Explaining why these tracers park and at what rate they reach the shore has important implications on a variety of different nearshore environmental issues, including the determination of what subscale processes are essential in computer models for the simulation of pollutant transport in the nearshore. Using a simple model we provide an explanation for the underlying mechanism responsible for the parking of tracers, not subject to inertial effects, the role played by the bottom topography, and the non-uniform dispersion which leads, in some circumstances, to the eventual landing of all or a portion of the tracers. We refer to the parking phenomenon in this environment as nearshore sticky waters.

1. Introduction

Oil from spills, red tides, flotsam and other suspended and surface tracers approach the nearshore, carried by winds and currents. It is not uncommon, however, that these debris and tracers slow down and park themselves, somewhere beyond the break zone (See Fig. 1); eventually, a portion of these reach the beach zone by the action of turbulence and tidal effects, in combination with inertial effects on the debris. The tendency of tracers to park themselves in certain areas of the Great Barrier Reef has been noted. Wolanski and Spagnol (2000), who reported the phenomenon, and denoted it as "sticky waters". Though we will not be discussing estuarine environments and the mechanism at play in the Great Barrier Reef situation may be different from the nearshore case, we will borrow this terminology and refer to the phenomenon we investigate in this paper as "nearshore sticky waters".

Of obvious environmental, economic, and social importance, understanding why nearshore sticky waters occur is also fundamental to improved environmental assessments of coastal settings. Moreover, as part of a larger research agenda aimed at improving models for pollutant transport in ocean general circulation models, nearshore sticky waters offers a field-verifiable problem with which to test contaminant advection reaction and dispersion models.

The focus is on tracer transport phenomena, with length scales several times larger than the depth and temporal scales of hours, weeks. That is, we are mostly concerned with large-scale pollution "disasters", such as large-scale red tides, significant oil spills, etc. Although we consider long time and space scales, we cannot ignore depth dependent features of the flow and the transport of tracers. The tracer may be buoyant but not necessarily entirely residing on the surface of the ocean; We therefore consider a layered (instead of simply depth averaged) model for the tracer and account for the vertical structure of the advective velocity. We defer consideration of tracers with non-trivial inertial effects to a separate study. Obviously, tracers advect and diffuse in the alongshore direction as well as in the cross-shore direction. In fact, advection/diffusion in the longshore direction is usually more intense in many non-estuarine environments. However, if we consider a situation where the longshore variations of the tracer concentrations are small, the divergence of the flux in the longshore direction is negligible, and it is appropriate to consider a one-dimensional problem in the cross-shore direction.

Nearshore sticky waters will refer to the slowing down or the parking of the tracer approaching the shore. In a sticky water situation the center of mass of the incoming tracer that is approaching the shore at advective speeds will experience a partial or total slowing down. Whatever tracer amounts reach the shore will do

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Fig. 1. A red tide event, off the coast of Florida. The event occurs nearly annually along the state's Gulf Coast. Image courtesy of P. Schmidt, Charlotte Sun. For an example that has more surfzone wave action, see Fig. 1 of Grant et al. (2005).

so by the action of dispersive effects, usually higher inside the breakzone than in deeper waters. In the cross-shore direction, large scale currents are typically weak, close to the shore. In a wave-dominated nearshore setting, the typical advection velocity would be the residual flow due to the waves, the Stokes drift velocity. The length scales are those of the long waves, *i.e.*, waves which have wavelengths that are large when compared to the depth. The diffusive length scale is typified by large-scale eddies; if the break zone is a significant source of mixing, the length scale would be the distance between the start of the breaking of the waves and the shore. When advective and diffusive effects are those in balance, the diffusive time scale is large, in the order of hours. There is consensus that in wave-dominated beaches the dissipation of waves is different inside and outside of the breakzone, the latter being considerably smaller than the former. Mei (1989), Chapter 10, describes the theoretical development of a model for wave action dissipation, based upon dimensional analysis and homogeneous turbulence concepts (see also Svendsen and Putrevu, 1994, for further developments). The model used in Uchiyama et al. (2009) is that of Thornton and Guza (1983), which is one of several based upon hydraulic jump parametrizations. Analysis of field data of the dispersion of tracers in the nearshore suggest that the diffusivity is much higher in the break zone than outside. Dispersion estimates based upon the dimensional analysis model of Svendsen and Putrevu (1994) are off by orders of magnitude, when compared to field data (see Feddersen, 2012a). A possible explanation for the discrepancy might lie in the fact that the dimensional parametrization is based upon homogeneous turbulence conditions and is more typical of the smaller scale vertical diffusion, rather than the larger eddy-scale transverse diffusion (Feddersen, private communication).

The basic depth-averaged hydrodynamics, appropriate to these scales, are captured by the similarly scaled vortex force model in McWilliams et al. (2004) (see McWilliams and Restrepo, 1999; Restrepo, 2001 for background and Lane et al., 2007 for a comparison of this "vortex force" model and the "radiation stress" alternative. See also Smith (2006)). In the following form, the model has been used to study nearshore problems, such as longshore currents (in Uchiyama et al., 2009), and rip currents (in Weir et al., 2011). The depth-averaged momentum balance reads:

$$\frac{D\mathbf{v}^c}{Dt} = -g\nabla\zeta - \chi[\mathbf{u}^{St}]^{\perp} + \mathbf{N}, \tag{1}$$

where χ is the vorticity of the depth-averaged velocity $\mathbf{v}^c(x,y,t) := (u^c, v^c)$, and $\mathbf{N}$ encompasses bottom drag, wind forcing, and dissipation; it also encompasses momentum transfers from wave breaking to the current momentum (see Restrepo et al., 2011). The vortex force is the second term on the right hand side, which couples the residual flow due to the waves to the rotation in the current $\mathbf{v}^c$. The depth-averaged Stokes drift velocity is denoted by $\mathbf{u}^{St} := (u^{St}, v^{St})$; the operator $\perp$ is used to obtain $[\mathbf{u}^{St}]^{\perp} = (-v^{St}, u^{St})$.

The continuity equation reads

$$\frac{\partial\zeta}{\partial t} = -\frac{\partial\zeta^c}{\partial t} - \nabla\cdot[\mathcal{H}(\mathbf{v}^c + \mathbf{u}^{St})], \tag{2}$$

where $\mathcal{H} = \zeta^c + H(x,t)$ is the local water column depth and $\zeta^c = \zeta + \hat{\zeta}$ is the composite sea elevation; $\hat{\zeta}$ is the quasi-static sea elevation. The waves are found via conservation equations for the wave action $\mathcal{A}$, and wavenumber $\mathbf{k}$. For the wave action, the equation is

$$\frac{\partial\mathcal{A}}{\partial t} + \nabla\cdot(\mathbf{C}_G\mathcal{A}) = N_{\mathcal{A}}, \tag{3}$$

where $N_{\mathcal{A}}$ is the loss term and $\mathbf{C}_G$ is the absolute group velocity,

$$\mathbf{C}_G = \mathbf{v}^c + \frac{\Sigma}{2k^2}\left(1 + \frac{2k\mathcal{H}}{\sinh 2k\mathcal{H}}\right)\mathbf{k}. \tag{4}$$

The relative frequency is $\omega = \mathbf{v}^c\cdot\mathbf{k} + \Sigma$, where the frequency satisfies the dispersion relation $\Sigma = \sqrt{gk\tanh(k\mathcal{H})}$. The wave action, the Stokes drift velocity and the quasi-static sea elevation response are given by

$$\mathcal{A} := \frac{1}{2\Sigma}\rho g A^2, \quad \mathbf{u}^{St} := \frac{1}{\rho\mathcal{H}}\mathcal{A}\mathbf{k}, \quad \hat{\zeta} = -\frac{A^2k}{2\sinh(2k\mathcal{H})}, \tag{5}$$

respectively. A is the wave amplitude and k is the magnitude of the wavenumber $\mathbf{k}$. The wavenumber conservation equations are

$$\frac{\partial\mathbf{k}}{\partial t} + \nabla(\Sigma + \mathbf{v}^c\cdot\mathbf{k}) = 0. \tag{6}$$

The evolution equation for a tracer θ, (see McWilliams et al., 2004), is

$$\frac{\partial\theta}{\partial t} + (\mathbf{v}^c + \mathbf{u}^{St})\cdot\nabla\theta = N_\theta, \tag{7}$$

where N_θ is the tracer dispersion term.

The simplest situation we consider is that of a flow with mean shoreward-directed velocity, transporting the pollutant toward land, flowing over a sloped and featureless bathymetry. We consider a nearshore domain that has only transverse extent x and depth z; the water column increases in depth, away from the shore. Consideration of the actual mechanism that is generating the current field makes the basic story presented here richer, but is beyond the scope of this paper. Instead we focus on the basic kinematics of the tracers.

The advecting mean current, with a shore-directed component, might consist entirely or partially of a wave-induced flow, the Stokes drift velocity (see Mei, 1989). For specificity we will assume, in fact, that the advective mean current is exclusively composed of the Stokes drift and that these are generated by shore-directed waves. (As the reader will eventually surmise we could have assumed instead the presence of currents not associated with waves, or even considered the case where both wave-induced flows and currents are present; nearshore sticky waters conditions do not require the presence of wave-generated currents). According to (1), however, this Stokes drift will not generate a vortex force. If the velocity at the shore end, at $x = 0$, is zero, the cross-shore component of the depth-averaged current $u^c(x,t)$ must be equal and opposite to the cross-shore component of the depth-averaged Stokes drift velocity (in Uchiyama et al., 2009 we recognized it as the *anti-Stokes* current, but more generally it is the undertow current. See Lentz and Fewings, 2012 for more details