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Diurnal sea breeze effects on inner-shelf cross-shore exchange

John Hendrickson, Jamie MacMahan *

Oceanography Department, Naval Postgraduate School, Monterey, CA 93933, USA

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ABSTRACT

Cross-shore exchange by strong (cross-shore wind stress, $\tau_{sx}>0.05$ Pa) diurnal (7–25 h) sea breeze events are investigated using two years of continuous wind, wave, and ocean velocity profiles in 13 m water depth on the inner-shelf in Marina, Monterey bay, California. The diurnal surface wind stress, waves, and currents have spectral peaks at 1, 2, and 3 cpd and the diurnal variability represents about 50% of the total variability. During sea breeze relaxation ($-0.05<\tau_{sx}<0.05$ Pa), a background wave-driven inner-shelf Eulerian undertow profile exists, which is equal and opposite to the Lagrangian Stokes drift profile, resulting in a net zero Lagrangian transport at depth. In the presence of a sea breeze ($\tau_{sx}>0.05$ Pa), a uniform offshore profile develops that is different from the background undertow profile allowing cross-shore Lagrangian transport to develop, while including Lagrangian Stokes drift. The diurnal cross-shore current response is similar to subtidal (>25 h) cross-shore current response, as found by Fewings et al. (2008). The seasonality of waves and winds modify the diurnal sea breeze impact. It is suggested that material is not transported cross-shore except during sea breeze events owing to near zero transport during relaxation periods. During sea breeze events, cross-shore exchange of material appears to occur onshore near the surface and offshore near the sea bed. Since sea breeze events last for a few hours, the long-term cross-shore transport is incremental each day.

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1. Introduction

Cross-shore transport plays a significant role in the allocation and redistribution of phytoplankton, nutrients, sediment and pollutants across the continental shelf and the surf zone. Continental shelf ecosystems are some of the most dynamic on earth (Falkowski et al., 1998). Near the continental shelf break, upwelling forces nutrient-rich water to the surface causing high biological productivity, which is then transported across the continental shelf (Pilskaln et al., 1996; Ryan et al., 2009). Therefore, it is important to understand the mechanisms responsible for cross-shore exchange. There are three primary regions located shoreward of the outer continental shelf, which are referred to as the mid-shelf, inner-shelf and surf zone, and are dominated by different dynamics (Lentz et al., 1999).

For the mid-shelf, cross-shore transport is the result of steady alongshore wind stresses acting together with the Coriolis force producing a transport of water at a right angle to the predominant wind direction in the Northern Hemisphere, known as Ekman transport (Ekman, 1905; Sverdrup, 1938; Csanady, 1978; Lentz, 1992; Dever, 1997; Lentz et al., 1999). On the mid-shelf, during upwelling or downwelling events, the mid-water pycnocline intersects the surface or bottom boundary, forming a front that moves offshore. During both upwelling and downwelling, full Ekman transport develops in the mid-shelf region because the strong stratification of the pycnocline acts to insulate the surface and bottom layers from each other (Lentz et al., 1999; Austin and Lentz, 2002). The region seaward of this dynamic front is the mid-shelf and the region shoreward of the front is the inner-shelf (Lentz, 1994; Lentz et al., 1999; Austin and Lentz, 2002).

On the inner-shelf, as the water depth decreases, the alongshore surface stress becomes increasingly balanced by the bottom stress instead of the Coriolis force, reducing Ekman surface boundary layer transport (Dever et al., 2006). Numerical modeling studies (Austin and Lentz 2002; Tilburg, 2003) and observations on the inner-shelf regions of North Carolina (Lentz et al., 1999; Lentz, 2001), Massachusetts (Fewings et al., 2008), Oregon (Kirincich et al., 2005) and California (Cudaback et al., 2005) found that alongshore winds are not a sufficient mechanism in driving cross-shore exchange on the inner-shelf. Tilburg (2003) numerically found that onshore winds induced a two-layer flow consisting of onshore transport near the sea surface and an equal and opposite offshore transport below that allowed for cross-shore exchange.

The surf zone is defined as the region between depth-limited breaking (Thornton and Guza, 1983) and the shoreline. The mechanisms for cross-shore transport in the surf zone are wave-driven and consist of Stokes drift, undertow, and rip currents. Stokes drift is the time-averaged, second-order velocity of a particle under a wave. There is an incomplete closure of the

* Corresponding author.
E-mail address: jhmacmah@nps.edu (J. MacMahan).

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particle path after each wave period resulting in a net drift in the direction of wave propagation (Stokes, 1847). The associated mass transport occurs between the wave trough and crest in the Eulerian reference frame and is vertically distributed below mean sea level (MSL) in the Lagrangian reference frame. The theoretical cross-shore Stokes transport, Q_{stokes}, is the same in the Lagrangian and Eulerian reference frames and given by

$$Q_{stokes} = \frac{gH_{mo}^2}{16c}\cos\theta_w, \quad (1)$$

where g is the gravitational acceleration, H_{mo} is the significant wave height, c is the phase speed of the waves, and θ_w is the wave direction relative to shore-normal (Stokes, 1847; Longuet-Higgins, 1953).

The onshore transport near the surface is balanced by an equal transport in the opposite direction at depth, the undertow (Ursell, 1950; Haines and Sallenger, 1994; Garcez Faria et al., 2000; Reniers et al., 2004). In the surf zone, the compensating return 2D vertical profile is parabolic with a maximum offshore flow at mid-depth and close to wave breaking (Haines and Sallenger, 1994; Garcez Faria et al., 2000; Reniers et al., 2004).

Undertow represents the 2D vertical velocity profile, while rip currents represent the 2D horizontal circulation (assuming the vertical velocity profile is depth-uniform in the surf zone; Haas and Svendsen, 2002; MacMahan et al., 2005) allowing for transport of material across the surf zone. Alongshore bathymetric variations create alongshore variations in depth-limited wave breaking that induce alongshore gradients in pressure and momentum driving water from the shore-connected shoals toward rip channels (Bowen, 1969; Dalrymple, 1978). Onshore flows over the shore-connected shoals or bars transition to alongshore flows (feeder currents) near the shoreline that converge in the rip channel and extend seaward across the surf zone, and beyond (Shepard et al., 1941; Inman and Brush, 1973; MacMahan et al., 2009).

1.1. Mechanisms for cross-shore transport on the inner-shelf

Hasselmann (1970) suggested that the Coriolis force acting on the surface wave flow induces a small along-crest wave velocity that is in-phase with the vertical wave velocity resulting in a "wave stress". Xu and Bowen (1994) theoretically determined that the "Hasselmann" wave stress is balanced by the Coriolis force in the alongshore momentum balance, resulting in an offshore-directed Eulerian flow, which is equal and opposite to the Lagrangian Stokes drift, resulting in a zero net transport over the vertical as suggested by Ursell (1950) (Fig. 1a–c). This explains why the ocean does not pile up water against the shoreline owing to the shoreward transport of Stokes drift. The presence of this compensating offshore-directed Eulerian flow has been observed outside of the surf zone in the field (Reniers et al., 2004; Smith, 2006; Lentz et al., 2008) and in the laboratory (Putrevu and Svendsen, 1993; Ting and Kirby, 1994; Cox and Kobayashi, 1997; Monosmith et al. 2007).

Lentz et al. (2008) compared the wave-driven velocity profiles from Martha's Vineyard Coastal Observatory, MVCO, to the theoretical work by Xu and Bowen (1994). The model by Lentz et al. (2008) assumes steady-state, linear dynamics, alongshore homogenous and constant density. The model is based on the continuity and momentum balances;

$$\int_{-h}^{0} u dz = -Q_{stokes}, \quad (2)$$

$$-fv = fv_{stokes} - g\eta_x - F^{ws} + \tau_{(bx)z}/\rho_o + \tau_{(sx)z}/\rho_o + (Au_z)_z, \quad (3)$$

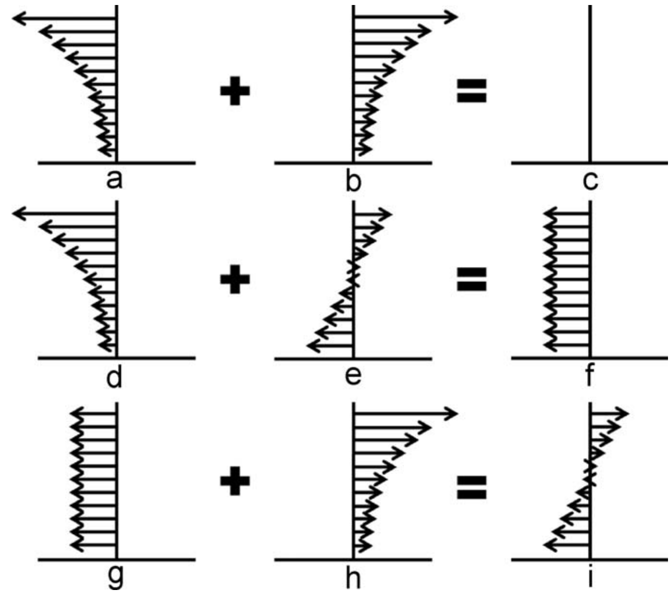

Fig. 1. Wave- and wind-driven velocity profiles (waves traveling left to right, onshore is to the right). (a) Eulerian wave-driven undertow profile, (b) Lagrangian Stokes drift velocity profile, (c) summed velocity profile of (a) and (b) resulting in zero net transport at depth; (d) Eulerian wave-driven undertow profile, (e) Eulerian wind-driven velocity profile, (f) combined (d+e) wave and wind-driven profile; (g) Eulerian combined wave and wind-driven profile, (h) Lagrangian Stokes drift velocity profile, (i) combined (g+h) profile results in onshore transport near the surface and offshore transport near the sea bed.

$$fu = -fu_{stokes} + \tau_{(by)z}/\rho_o + \tau_{(sy)z}/\rho_o + (Av_z)_z, \quad (4)$$

where f is the Coriolis frequency, u, v, w are the cross-shore, alongshore, and vertical velocities, u_{stokes}, v_{stokes} are Stokes velocities, x and z subscripts indicated cross-shore and vertical partial derivatives, y is the alongshore direction, F^{ws} is the momentum flux due to shoaling waves, τ_b is the cross- and alongshore bottom stress, ρ_o is the density of seawater, τ_s is the cross- and alongshore wind stress, and A is an eddy-viscosity used to parameterize Reynolds stresses (Lentz et al., 1999; see Lentz et al. (2008) for a detailed description of the model). Assuming continuity and a vertical varying eddy-viscosity, the model consists of three equations and three unknowns and is solved numerically (Lentz, 1995). For small eddy viscosities (indicative of motions outside the surf zone) the offshore velocity profiles have a curvature with a maximum offshore flow near the surface that decreases toward the bottom (Fig. 1a). These modeled profiles favorably matched the field observations at MVCO outside the surf zone. Lentz et al. (2008) concluded that in the absence of wind, the time-averaged flow in the inner-shelf is primarily associated with undertow that is driven by surface-gravity waves and influenced by the Hasselmann wave stress.

Prior to the work of Tilburg (2003), cross-shore winds were considered ineffective in forcing cross-shore transport due to the cross-shore components of the surface and bottom boundary stress being an order of magnitude smaller than the Coriolis force of the alongshore flow (Csanady, 1978; Allen, 1980). Fewings et al. (2008) observed that the cross-shore wind forcing was important for cross-shore exchange, as it modifies the wave-driven undertow profile found by Lentz et al. (2008) (Fig. 1d–f). The observed Eulerian flow below the wave trough was in the direction of wind forcing, consistent with previous estimates of surface wind-induced drift (Wu, 1983; Ogasawara and Yasuda, 2004), and a compensating return flow in the bottom portion of the profile was in the opposite direction of the wind forcing (Fig. 1e). Fewings et al. (2008) found that as background wave forcing increased, the