Lecture08-Inner_shelf_circulation

October 28, 2025

1 Lecture08 - Inner shelf circulation

Learning Objectives: surface vs bottom Ekman layer, along-shore wind-driven circulation, role of stratification, cross-shore wind-driven circulation, wave and wind driven: their relative importance depends on water depth

Before class:

- Read through session 2.4 California upwelling system in Lecture 07 and focus on the biogeochemical impact of upwelling.

After class:

- Read the article: Untangling a Web of Interactions Where Surf Meets Coastal Ocean, and explore the use of multiplatform, modern instrumentation and collaborative efforts in investigating the rich physical processes of the inner shelf.

Reference:

- Lentz and Fewings, 2011
- Austin and Lentz, 2002
- optional: Brink, 6.1-6.2, 6.4

The **inner continental shelf**, which spans water depths of a few meters to tens of meters, is a dynamically defined region that lies between the **surf zone** (where **waves break**) and the **middle continental shelf**(where the along-shelf circulation is usually in **geostrophic balance**). - Within the inner shelf, the surface and bottom boundary layers (e.g., Ekman layers) overlap and occupy the entire water column. - Many types of forcing that are often neglected over the deeper shelf, such as surface gravity waves and cross-shelf wind stress, can drive substantial circulations over the inner shelf. This lecture will discuss the roles of alongshelf wind and pressure gradients, cross-shelf wind, and surface gravity waves in driving innershlef circulation. - The width and location of the inner shelf vary in time, because the thicknesses of the surface and bottom boundary layers vary in time depending on the strengths of the wind and wave forcing and vertical density stratification. - Cross shelf velocities (2-4 cm/s) < alongshelf velocities (10-15 cm/s), but important for exchange.

1.1 1. Along-Shelf Wind Forcing

1.1.1 1). Cross-shelf circulation for unstratified water

Below is an example of **downwelling-favorable along-shelf wind stress** over an along-shelf uniform **unstratified** water column. The unstratified along-shelf response is **symmetric** with respect to wind stress direction, so reversing the wind stress to upwelling-favorable just reverses the circulation pattern. 1. In very shallow water (roughly h < 0.5 s), the stress is approximately constant throughout the water column so there is essentially no cross-shelf circulation and the flow is downwind, consistent with a nonrotating fluid. 2. The onshore **Ekman transport** near the surface results in a convergence in shallow waters (0.5 s < h < 2 s, where s_{Ekman} is the boundary-layer thickness) that initially causes sea level to rise toward the coast. 3. This sea level change leads to the **geostrophic setup** that results in a cross-shelf pressure gradient that drives a **geostrophic along-shelf flow**. 4. This geostrophic along-shelf flow is most evident outside of the innershelf where the surface (h > 2 s) and bottom boundary layers do not overlap so there is an **interior** region without turbulent stresses, the resulting cross-shelf pressure gradient **balances** a geostrophic along-shelf flow. 5. The **bottom stress** due to the geostrophic along-shelf flow drives the **offshore flow** (Ekman transport) in the **bottom boundary layer** that compensates for the onshore surface flow. 6. In shallow water where the surface and bottom boundary layers do overlap, the surface stress is transmitted directly to the bottom by turbulent momentum fluxes.

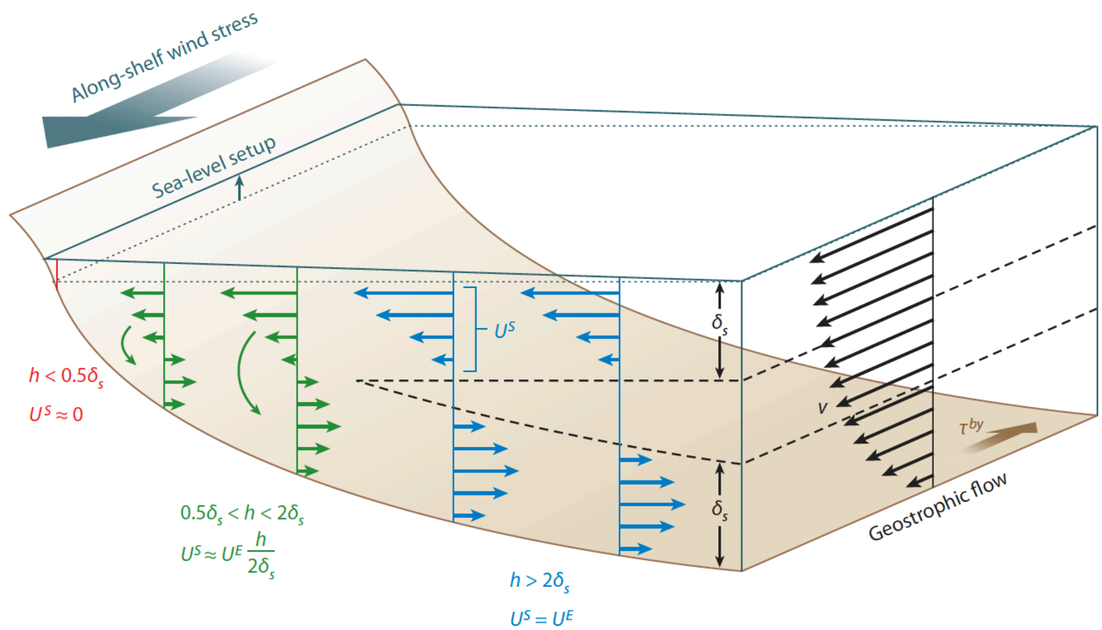

Figure 3

Schematic of the unstratified inner- and middle-shelf responses to an along-shelf wind stress, highlighting dynamical regions onshore and offshore of the locations where the surface and bottom boundary layers interact: very shallow water (*red*), intermediate region (*green*), and middle shelf (*blue*). The geostrophic setup of the sea level extends across the shelf. The water depth is h, the surface and bottom boundary-layer thicknesses are δ_s, the along-shelf velocity is v, the along-shelf component of the bottom stress is τ^{by}, the cross-shelf volume transport in the surface boundary layer is U^S, and the Ekman transport driven by the along-shelf wind in deep water is $U^E = \tau^{sy}/\rho_0 f$, where ρ_0 is the seawater density and f is the Coriolis parameter.

1.1.2 2). Stratified inner-shelf circulation

Stratification results in an **asymmetry** in the response to upwelling-favorable and downwelling-favorable wind stresses.

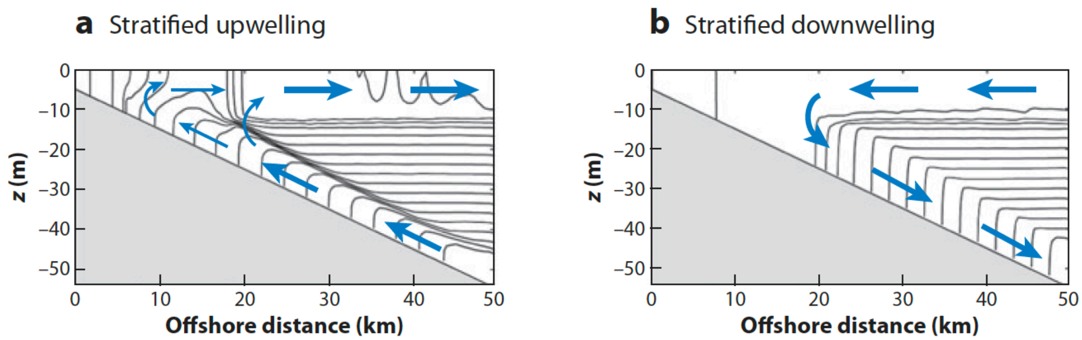

Figure 5

Schematics of the stratified inner- and middle-shelf responses to an along-shelf wind stress, highlighting the difference between (*a*) upwelling and (*b*) downwelling. The gray contours are lines of constant density. Blue arrows indicate cross-shelf circulation. Figure modified with permission from Austin & Lentz (2002).

a. Downwelling inner shelf

- For **downwelling-favorable winds** blowing over a stratified shelf, models suggest that the onshore flow in the surface boundary layer combines with vertical mixing to form an **unstratified inner-shelf region** where the cross-shelf circulation is shut down (Figure 5b).
- The shutdown of the cross-shelf circulation means that during downwelling on a stratified shelf, the inner shelf and surf zone are isolated from exchange with the stratified middle-shelf water.

The figure below shows drifters on the Oregon shelf during downwelling-favorable winds that were observed to stop moving onshore well away from the coast and instead moved in the along-shelf direction, consistent with these model predictions (Austin & Barth 2002).

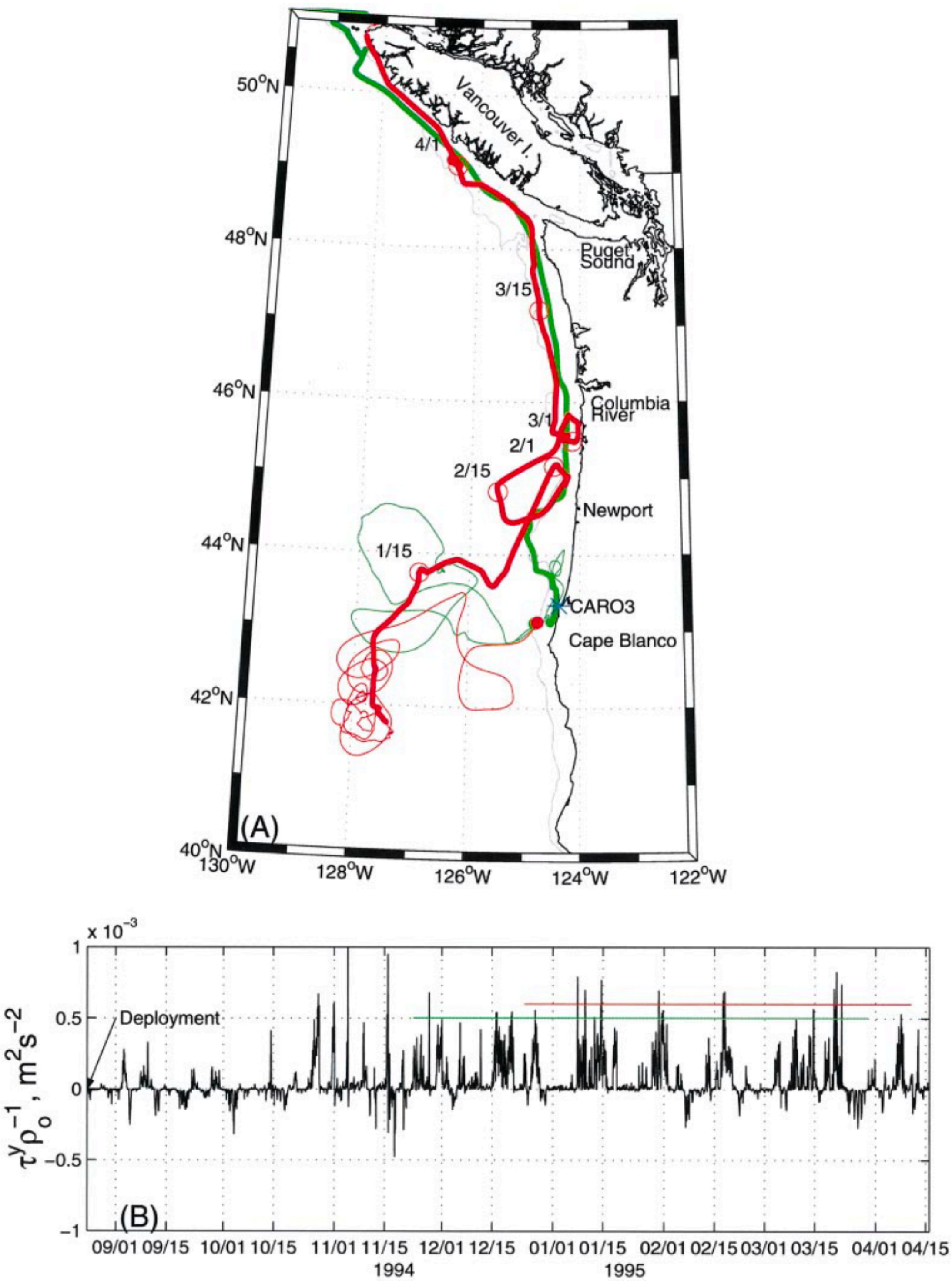

FIG. 2. (a) The paths of two drifters released on 24 Aug 1994 within 4 km of each other (green: 22251, red: 22252). The position of the CARO3 NDBC meteorological station is marked with a star. The filled colored dots represent the deployment positions. The open red circles are representative positions with dates of drifter 22252. The thickened lines correspond to the time periods shown in (b), and represent the portion of the time series when the drifters are moving rapidly onshore or poleward. The light gray line is the 200-m isobath. (b) The alongshelf wind stress at station CARO3. Positive is downwelling favorable. Red and green lines correspond to time periods of rapid onshore or poleward movement of the drifters.

b. Upwelling inner shelf

- For **upwelling-favorable winds** blowing over a stratified shelf, models again indicate that the middle shelf is separated by a front from an inner-shelf region with weaker stratification. In contrast to the downwelling case, the cross-shelf circulation onshore of the upwelling front is not completely shut down. Offshore of the front, there is offshore flow in the surface boundary layer and onshore flow in the bottom boundary layer (Figure 5a).
- **Stratification is maintained** onshore of the front because the density of the water transported onshore in the bottom boundary layer increases as it is drawn from deeper depths along the sloping bottom.
- The resulting stratification over the inner shelf, although weaker than the stratification offshore, allows the cross-shelf circulation to extend over the inner shelf. As a result, upwelling is spread over a broader portion of the inner shelf than downwelling.
- In these along-shelf uniform model simulations, the inner shelf is less isolated from the middle shelf during upwelling- than during downwelling-favorable wind stresses.

1.2 2. Cross-Shelf Wind Forcing

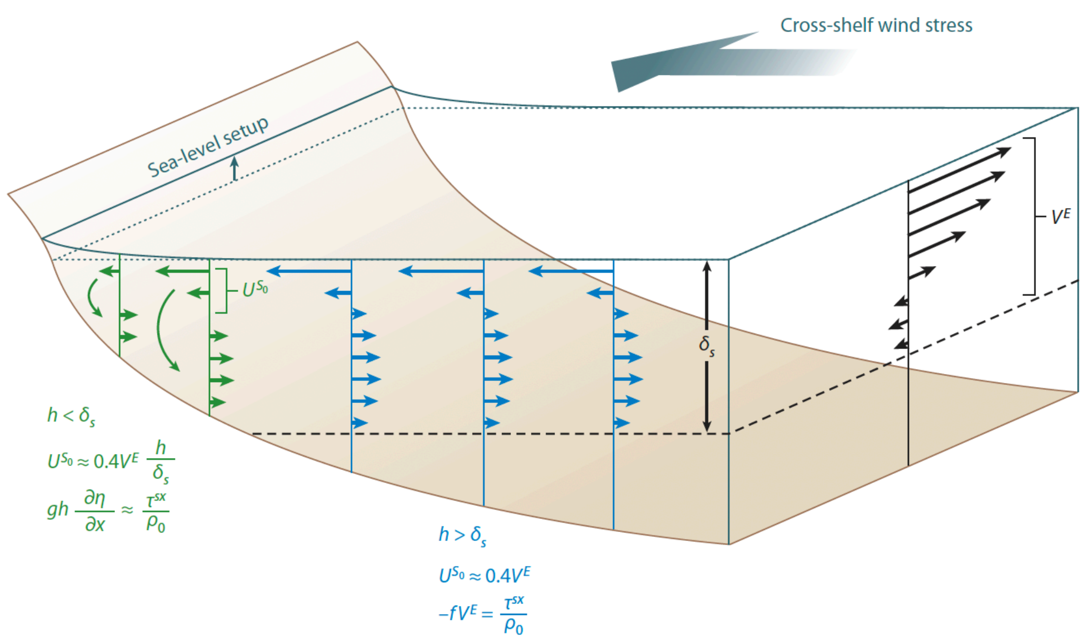

Figure 6

Schematic of the unstratified inner- and middle-shelf responses to a cross-shelf wind stress, highlighting two dynamical regions onshore and offshore of the location where the surface boundary layer intersects the bottom. The setup of the sea level is confined to the onshore region. The water depth is h, the surface boundary-layer thickness is δ_s, g is the acceleration due to gravity, η is the sea level, x is the cross-shelf coordinate, τ^{sx} is the cross-shelf wind stress, ρ_0 is the seawater density, f is the Coriolis parameter, the cross-shelf volume transport above the first zero crossing of the cross-shelf velocity profile is U^{S_0}, and the Ekman transport driven by the cross-shelf wind in deep water is $V^E = -\tau^{sx}/\rho_0 f$.

- In contrast to along-shelf winds, cross-shelf winds are ineffective at driving along-shelf flows.
- However, the cross-shelf wind can drive a **cross-shelf circulation** that extends all the way to the coast.
- An onshore wind stress over an along-shelf uniform unstratified continental shelf forces a

steady cross-shelf circulation that is confined to the **surface boundary layer**, with an onshore flow near the surface and an offshore return flow in the lower portion of the surface boundary layer (Figure 6).

- In water deeper than the surface boundary-layer thickness, the circulation due to the cross-shelf wind stress is the one-dimensional (1D) open ocean Ekman response. The circulation is confined to the surface boundary layer with a net **along-shelf (perpendicular to the wind stress) Ekman transport** and no net cross-shelf (downwind) transport in the surface boundary layer.

1.3 3. Wave-driven circulation

The tendency for the offshore flow forced by the waves to be equal in magnitude to the onshore Stokes drift velocity at each depth suggests that surface wave forcing results in nearly zero net cross-shelf Lagrangian transport of passive particles over the inner shelf.

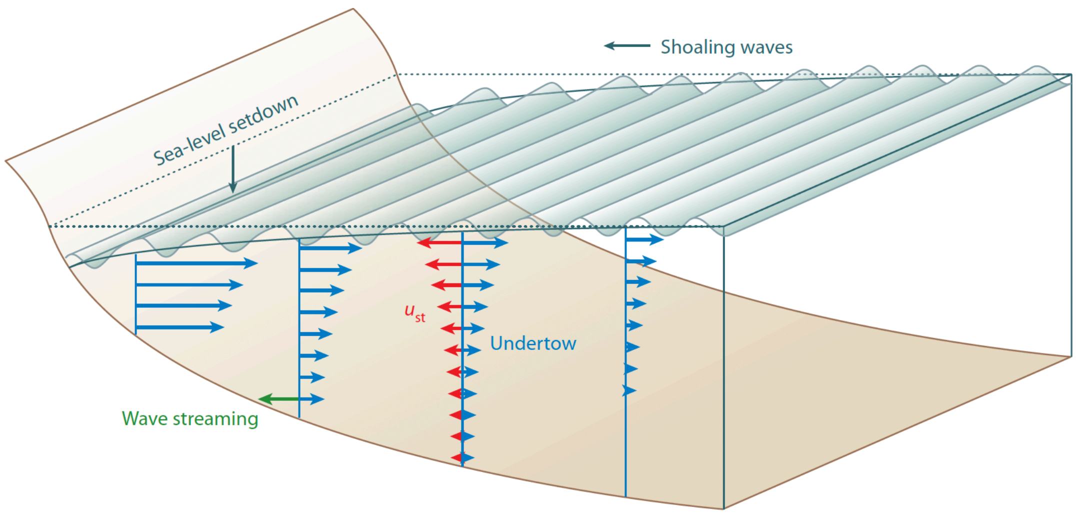

Figure 9

Schematic of the inner-shelf circulation forced by surface gravity waves, showing the response to Stokes-Coriolis forcing (*blue*) and wave-induced bottom streaming (*green*). Note that the surf zone and middle shelf are not shown. The Stokes drift (*red*) is not detected by Eulerian (fixed in space) measurements, such as those from acoustic Doppler current profilers, but is added to Eulerian measurements to estimate the net Lagrangian transport. Over the inner shelf, the Stokes drift $u_{st}(z)$ tends to cancel the Stokes-Coriolis-induced Eulerian velocity or undertow, suggesting that the net wave-driven transport is near zero over most of the water column.

1.4 4. Who's more important in driving inner-shelf circulation?

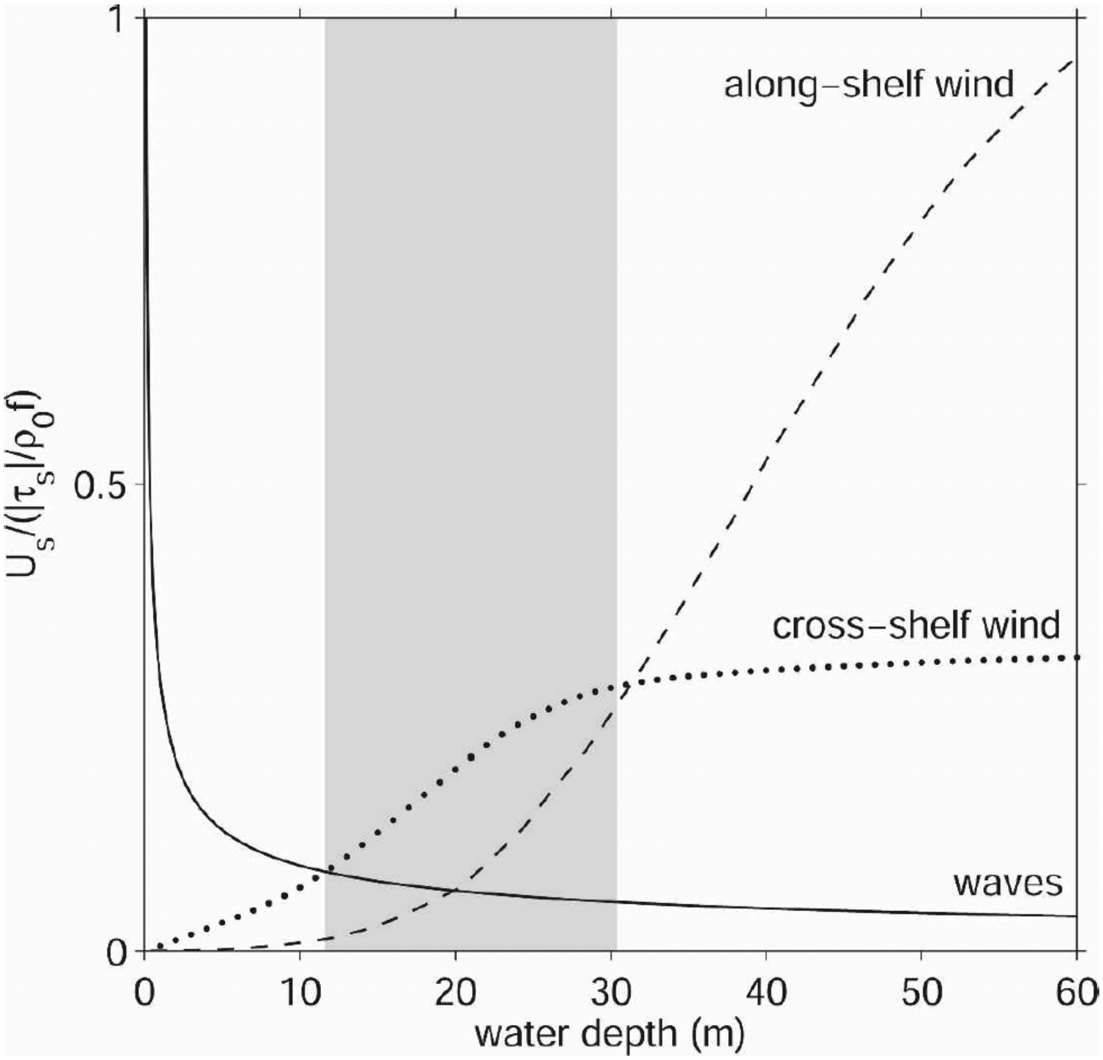

FIG. 15. Relative importance of cross-shelf wind stress, along-shelf wind stress, and wave forcing: theoretical cross-shelf surface layer transport U_s normalized by deep-water Ekman transport $|\boldsymbol{\tau}_s|/\rho_0 f$, as a function of water depth. The U_s is calculated numeri-

1.5 5. (additional content) Internal-wave driven circulation and the ISDE

Discussion: Read the article: Untangling a Web of Interactions Where Surf Meets Coastal Ocean, and explore the use of multiplatform, modern instrumentation and collaborative efforts in investigating the rich physical processes of the inner shelf.

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